PRINCIPLES OF COMBUSTION IN THE STEAM BOILER FURNACE

By
ARTHUR D. PRATT

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ARTHUR D. PRATT

BOSTON SOCIETY
CIVIL ENGINEERS

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INTRODUCTION

THE function of a boiler furnace is the generation of the maximum amount of heat from a given quantity of a specific fuel, and if such function is to be properly fulfilled, it is essential that the furnace operator understand the broader principles involved in combustion. Unfortunately, from the standpoint of efficient steam generation, the statement is too frequently accepted as true that theoretical generalizations and mathematical formulae are of but little value to the operating engineer. To an extent, such statements may be true, but on the other hand it is to be remembered that combustion is purely a chemical phenomenon and as such can be properly investigated and controlled only by chemical means. Experience resulting from the "cut and try" methods of ordinary actual practise in the burning of individual fuels is unquestionably an important factor in the bringing about of efficient furnace results, but it is obvious that such results will be most readily secured when this experience is combined with a full knowledge of the theory of combustion and the proper application of the available methods used in obtaining combustion data. Further, the importance of such knowledge is today greater than it has ever been. Most apparatus for the generation of power has reached a state of development where there is but little likelihood of any great increase in economy. The generally accepted types of steam boiler used in present day power plant practise have the inherent ability to absorb heat efficiently and from this standpoint may be included with the apparatus from which much more cannot be expected. If we accept this statement as true, the efficient generation of steam in the boiler proper becomes in reality a question of efficient combustion, and it is this phase of boiler practise—the efficient generation of heat in the boiler furnace—in which there is the greatest and in fact the only field for appreciable improvement.

Power plant owners are coming more and more to appreciate the necessity for intelligence in the boiler room—the reinforcing of experience in firing by a full knowledge of the theory of combustion—and in the growing number of plants where this need is realized suitable apparatus is installed for the determination

and checking of combustion results. In plants not so equipped, the possible savings due to the intelligent use of such apparatus and the proper application of the data so obtained in reducing preventable losses, are in the aggregate enormous.

THE CHEMISTRY OF COMBUSTION

THE chemistry of combustion as applied to boiler furnace practise is elementary but for a proper comprehension of the subject it seems advisable to include a brief consideration of the general principles involved, together with data covering the combining qualities of the constituents of the fuels ordinarily encountered in steam generation.

The smallest quantity of an element or a compound that is capable of separate existence is taken as the physical unit of matter and is called a molecule. Molecules are composed of atoms of elements which may be defined as the smallest unit of an element which can enter into or be expelled from a compound. Atoms never exist singly but in combination with one or more atoms to form a molecule. Molecules of the elementary gases such as oxygen, nitrogen and hydrogen, are supposed to consist of two atoms.

A chemical reaction between elements or compounds is a rearrangement of the atoms of the constituent elements into a new combination of molecules. Such reactions always occur in accordance with fixed and invariable weight relations which are characteristic of the elements involved, and definite volumetric changes based on the number of gaseous molecules reacting and produced.

Elements are designated by symbols, and compounds by combinations of the symbols of their constituent elements. Subscripts are affixed to the symbols to designate the number of times the combining or atomic weight of the element occurs. It follows that from the symbol of a compound so expressed and the atomic weight of the elements involved, the proportionate parts by weight of the various constituents entering into the compound may be readily determined.

The elementary substances encountered in combustion work are oxygen, nitrogen, hydrogen, carbon and sulphur. The symbols of these elements together with their atomic weights are given in Table 1.

Combustion

Combustion is the phenomenon resulting from any chemical combination evolving heat. Oxygen is the sole supporter of

combustion, and a combustible therefore may be defined as a substance capable of combining with oxygen to produce heat. The speed of combustion depends upon the affinity of the combustible element for oxygen, and to a lesser extent upon the conditions under which combustion takes place. This speed may vary from the very slow, as in the case of rust formation, to the instantaneous, as in the explosion of confined powder.

From the standpoint of heat production for steam generating purposes, combustion may be defined as the rapid combination of the combustible elements of fuel with oxygen, while in this sense the term combustible implies the capacity of an element for combining rapidly with oxygen to produce heat.

Combustion is said to be complete when the combustible elements and compounds have united with all of the oxygen with which they are capable of entering into combination.

TABLE 1

ELEMENTS AND COMPOUNDS ENCOUNTERED IN COMBUSTION

Substance	Molecular Symbol	Automic Weight		Molecular Weight		Form
		Accurate	Approximate	Accurate	Approximate	
Carbon	C*	12.005	12	†	. . .	Solid
Hydrogen	H_2	1.008	1	2.015	2	Gas
Oxygen	O_2	16.00	16	32.00	32	Gas
Sulphur	S_2	32.07	32	64.14	64	Solid
Nitrogen‡	N_2	14.01	14	28.02	28	Gas
Carbon Monoxide	CO	. . .	. . .	28.01	28	Gas
Carbon Dioxide	CO_2	. . .	. . .	44.01	44	Gas
Methane	CH_4	. . .	. . .	16.03	16	Gas
Acetylene	C_2H_2	. . .	. . .	26.03	26	Gas
Ethylene	C_2H_4	. . .	. . .	28.03	28	Gas
Ethane	C_2H_6	. . .	. . .	30.05	30	Gas
Sulphur Dioxide	SO_2	. . .	. . .	64.07	64	Gas
Hydrogen Sulphide	H_2S	. . .	. . .	34.08	34	Gas
Water Vapor	H_2O	. . .	. . .	18.02	18	Vapor
Air	. . .	. . .	. . .	28.94	29	Gas

*Atomic symbol.

†The molecular weight of C has not been definitely determined. Carbon exists in a number of forms each of which probably has its own molecular weight. The latest investigations indicate that a molecule of carbon in any form consists of at least 12 atoms.

‡Atmospheric nitrogen as distinguished from chemically pure nitrogen which has an atomic weight slightly less than 14.01.

For the commercial production of heat it is essential that the combustible elements have a strong and ready affinity for oxygen. Carbon and hydrogen which are by far the most important of combustible elements encountered in the common fuels meet this requirement admirably. These occur either in a free or combined state in all fuels, liquid, solid and gaseous.

The combustible elements and the compounds in which they appear in any of the fuels used for commercial heat generation are given in Table 1. This table gives the symbols of the elements and their compounds which occur in combustion work together with their molecular weights. It also includes the non-combustible elements and compounds, a knowledge of which is necessary in the obtaining and application of combustion data.

Air

As we find in nature the combustible matter for the generation of heat, so from the same source we obtain, in the oxygen of the air, the necessary supporter of combustion.

Atmospheric air is a mechanical mixture—as distinguished from a chemical compound—of oxygen, nitrogen, and slight amounts of carbon dioxide, water vapor, argon and other inert gases. For engineering purposes the carbon monoxide and the inert gases are ordinarily included with the nitrogen and of the slightly varying proportions of oxygen and nitrogen given by different authorities the generally accepted values are :

	By Volume Per Cent	By Weight Per Cent
O_2	20.91	23.15
N_2	79.09	76.85

The oxygen with its strong affinity for the combustible constituents of the fuel, under the proper conditions of temperature which will be discussed hereafter, separates itself from its mechanical union with nitrogen and enters into chemical combination with the available combustible, thus fulfilling its function in the promotion of combustion. The nitrogen serves no purpose in combustion and in fact is a source of direct loss in that it absorbs heat in its passage through the furnace and carries off a portion of such heat in leaving the boiler; further, as a useless constituent it necessitates in the design of the furnace, boiler

and flue, space for its accommodation, which, were it possible or practicable to supply oxygen alone to the fuel, would not be required.

The combination of oxygen with the combustible elements and compounds is, as stated, in accordance with fixed laws. Considered as a chemical reaction the manner of such combination is simple and may be readily computed from the molecular weights given in Table 1. Assuming complete combustion and that the exact amount of oxygen required is supplied and utilized in combination, these reactions and the resulting combinations are as given in Table 2.

TABLE 2

CHEMICAL REACTIONS OF COMBUSTION

Combustible Substance	Reaction
Carbon (to CO)	$2C + O_2 = 2CO$
Carbon (to CO_2)	$2C + 2O_2 = 2CO_2$
Carbon Monoxide	$2CO + O_2 = 2CO_2$
Hydrogen	$2H_2 + O_2 = 2H_2O$
Sulphur (to SO_2)	$S + O_2 = SO_2$
Sulphur (to SO_3)	$2S + 3O_2 = 2SO_3$
Methane	$CH_4 + 2O_2 = CO_2 + 2H_2O$
Acetylene	$2C_2H_2 + 5O_2 = 4CO_2 + 2H_2O$
Ethylene	$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O$
Ethane	$2C_2H_6 + 7O_2 = 4CO_2 + 6H_2O$
Hydrogen Sulphide	$2H_2S + 3O_2 = 2H_2O + 2SO_2$

It is important to note from this table that carbon may enter into combination with oxygen to form two compounds, carbon monoxide and carbon dioxide. In burning to carbon monoxide, carbon has not combined with all of the oxygen with which it is capable of entering into combination and is not therefore completely oxidized. In burning to carbon dioxide it has combined with all of the oxygen possible and oxidization is complete. Carbon monoxide may unite with an additional amount of oxygen to form carbon dioxide and in this way the carbon of the original combination may become completely oxidized. The fact that carbon may enter into these two combinations with oxygen is of the greatest importance in furnace efficiency and will be discussed hereafter at greater length in the consideration of the heat of combustion and air supply.

Temperature

Before discussing in detail the effects of supplying oxygen for combustion in excess of the requisite amount or of supplying less than the amount required, the other important factor of combustion, viz., temperature, should be considered.

The speed of combustion is, as stated, dependent upon the affinity of the combustible matter for oxygen and the conditions under which combustion takes place. The chief of these conditions is that of temperature. The mere fact that oxygen is brought into the presence of a combustible substance does not of necessity mean that combustion will follow.

Every combustible substance has a temperature called its ignition temperature to which it must be brought before it will unite in chemical combination with oxygen and below which such combination will not take place; and this ignition temperature must exist with oxygen present or there will be no combustion.

The ignition temperature of different combustible substances varies greatly. These temperatures for various fuels and for the combustible constituents of the fuels used in boiler practise are given in Table 3.

TABLE 3

IGNITION TEMPERATURES

Combustible Substance	Molecular Symbol	Ignition Temperature Degrees Fahrenheit
Sulphur	S_2	470
Fixed Carbon—Bituminous Coal	. . .	766
Fixed Carbon—Semi-bituminous Coal	. . .	870
Fixed Carbon—Anthracite Coal	. . .	925
Acetylene	C_2H_2	900
Ethane	C_2H_6	1000
Ethylene	C_2H_4	1022
Hydrogen	H_2	1130
Methane	CH_4	1202
Carbon Monoxide	CO	1210

It is of interest to note that the temperature of ignition of the gases of a coal vary from each other (see flame) and are considerably higher than the ignition temperature of the fixed carbon of the coal. The ignition temperature of coal is the ignition temperature of its fixed carbon content, since the gaseous

constituents are ordinarily distilled off, though not ignited, before such temperature is attained.

When combustion has started, the heat evolved in the oxidization of the combustible matter will maintain under proper conditions sufficiently high temperatures for further ignition.

DENSITY WEIGHT AND VOLUME OF GASES

IN the computation of combustion data it is frequently necessary to know the density, weight and volume of air and of the various gases encountered in commercial practise.

The density of a gas (commonly expressed by the symbol $\triangle$) which is ordinarily referred to that of air as standard, is the weight of unit volume of the gas divided by the weight of an equal volume of pure dry air, the conditions of temperature and pressure being the same.

The weight per cubic foot of a gas, ordinarily designated by S, is, under standard conditions, called the specific weight. With the weight of air at atmosphere pressure and varying temperature conditions known, the weight of any gas at the same temperature may be computed from the relations of density and specific weight as indicated by

$$S_t = S_t \text{ (air)} \times \triangle \qquad (1)$$

the subscripts t simply indicating that the air and the gas, the weight of which is required, are at the same temperature.

The specific volume of a gas, usually designated by the symbol V, or the cubic feet per pound, will obviously be the reciprocal of its specific weight, or

$$V_t = \frac{1}{S_t} \qquad (2)$$

While it is perhaps easier and more convenient to compute weight and volumetric data of gases from their relative densities and a table of weights and volumes of air, such values may be computed from the characteristic equation of a perfect gas, viz:

$$PV = RT \qquad (3)$$

where P=absolute pressure in pounds per square foot,

V=volume per pound in cubic foot,

T=absolute temperature,

R=a constant varying with the gas and derived from the relations existing between the pressure, volume and temperature of the gas in question.

This pressure-volume-temperature relation for any gas, as indicated by the constant R, represents the expression

$$R = \frac{P_0 V_0}{T_0} \qquad (3\text{-}a)$$

where the subscripts $_0$ represent a set of standard conditions. Since the volume (and hence the specific weight) of a gas is a function of both temperature and pressure, it is necessary, in order that there may be a suitable basis for comparison, that all volumes be reduced to some such standard set of conditions. These conditions, as ordinarily accepted, are a pressure of 14.6963 pounds per square inch (2116.27 pounds per square foot) and a temperature of 32 degrees Fahrenheit.

Table 4 gives the weights and volumes of air at atmospheric pressure and different temperatures.

TABLE 4

VOLUME AND WEIGHT OF AIR

AT ATMOSPHERIC PRESSURE

Temperature Degrees Fahrenheit	Volume One Pound Cubic Foot	Weight per Cubic Foot Pounds	Temperature Degrees Fahrenheit	Volume One Pound Cubic Foot	Weight per Cubic Foot Pounds	Temperature Degrees Fahrenheit	Volume One Pound Cubic Foot	Weight per Cubic Foot Pounds
32	12.390	.080710	160	15.615	.064041	340	20.151	.049625
50	12.843	.077863	170	15 867	.063024	360	20.655	.048414
55	12.969	.077107	180	16.119	.062039	380	21.159	.047261
60	13.095	.076365	190	16.371	.061084	400	21.663	.046162
65	13.221	.075637	200	16.623	.060158	425	22.293	.044857
70	13.347	.074923	210	16.875	.059259	450	22.923	.043624
75	13.473	.074223	212	16.925	.059084	475	23.554	.042456
80	13.599	.073535	220	17.127	.058388	500	24.184	.041350
85	13.725	.072860	230	17.379	.057541	525	24.814	.040300
90	13.851	.072197	240	17.631	.056718	550	25.444	.039302
95	13.977	.071546	250	17.883	.055919	575	26.074	.038352
100	14.103	.070907	260	18.135	.055142	600	26.704	.037448
110	14.355	.069662	270	18.387	.054386	650	27.964	.035760
120	14.607	.068460	280	18.639	.053651	700	29.224	.034219
130	14.859	.067299	290	18.891	.052935	750	30.484	.032804
140	15.111	.066177	300	19.143	.052238	800	31.744	.031502
150	15.363	065092	320	19.647	.050898	850	33.004	.030299

With the values of P_0 and T_0 thus fixed (see Absolute Temperature below) the value of the constant R for any gas as given in formula (*3-a*) may be expressed as

$$R=\frac{2116.27}{459.64+32}V_0=4.3045\ V_0 \qquad (3\text{-}b)$$

thus offering a means of determining the value of R directly from the specific volume of the gas. Since the specific volume of a gas is the reciprocal of the weight per cubic foot, and for any two gases the weights per cubic foot vary inversely as their molecular weights, where the value of R for any gas is known, the value for any other gas may thus be determined from the relations of the molecular weights of the two gases, viz:

N_2—Molecular Weight=28 R=55.13
O_2—Molecular Weight=32 R=x

$$55.13 : x :: 32 : 28$$
$$R\ (O_2)=48.24$$

From the value of R as given in formula (*3-b*) it is possible to express the characteristic equation of a perfect gas in what is perhaps a more convenient form for general use, as

$$\frac{PV}{T}=\frac{P_0V_0}{T_0} \qquad (3\text{-}c)$$

From the characteristic equation (*3*), of a perfect gas, it is obvious that the volume of a gas will vary inversely as the absolute pressure and directly as the absolute temperature. In combustion work the variation in the pressure of the gases encountered is small. The temperature range covered, however, is large, and because of the effect of temperature change on volume, it is perhaps well to define here "absolute temperature."

Experiment shows that if the temperature of a perfect gas at 32 degrees Fahrenheit is increased one degree, the pressure being kept constant, the gas expands $\frac{1}{491.64}$ part of its volume. If such a rate of expansion per one degree increase in temperature held good at all temperatures, and experiment shows that such is the case above 32 degrees, if its pressure is kept constant, the gas would double in volume with an increase in temperature above 32 degrees of 491.64 degrees Fahrenheit. Under a reduction of temperature of 491.64 seconds below 32 degrees (corresponding to an

ultimate temperature of 491.64—32=459.64 degrees Fahrenheit below zero) the gas would disappear. While undoubtedly some change in the law would occur before the lower temperature could be reached, there is no reason why the law may not be used over the temperature range in which it is known to hold.

Table 5 gives the densities, weights and volumes under standard conditions, of the commercial gases encountered in combustion problems, as well as the values of the constant R.

TABLE 5

DENSITY, WEIGHT AND VOLUME OF GASES

AT ATMOSPHERIC PRESSURE AND 32 DEGREES FAHRENHEIT

Substance	Molecular Symbol	Relative Density		Weight per Cubic Foot Pounds	Cubic Feet per Pound Cubic Foot	Value of Constant R in PV=RT
		Air=1	Hydrogen=1*			
Air		1.0000		.08071	12.390	53.33
Oxygen	O_2	1.1053	16	.08921	11.209	48.24
Hydrogen	H_2	0.0696	1	.00562	177.936	765.8
Nitrogen	N_2	0.9673	14	.07807	12.809	55.13
Carbon Monoxide	CO	0.9672	14	.07806	12.811	55.15
Carbon Dioxide	CO_2	1.5291	22	.12341	8.103	34.88
Methane	CH_4	0.5576	8	.04500	22.222	95.64
Acetylene	C_2H_2	0.9200	13	.07425	13.468	57.97
Ethylene	C_2H_4	0.9674	14	.07808	12.807	55.12
Ethane	C_2H_6	1.0494	15	.08470	11.806	50.81
Sulphur Dixoide	SO_2	2.2639	32	.18272	5.473	23.56
Carbon† ‡	C			145	.0069	
Sulphur	S			125	.0080	

*Based on approximate molecular weights.

†Solid.

‡If carbon can be conceived to exist as a gas under standard conditions its relative density would be 0.820, its weight per cubic foot .0668 pounds, and its volume 14.97 cubic feet per pound.

From the foregoing it is evident that under a constant pressure, the volume of a gas will vary directly as the number of degrees between its temperature and the temperature—459.64 degrees Fahrenheit. To simplify the application of the law, a new thermometric scale is constructed, the point corresponding to —460 degrees Fahrenheit being taken as the zero point, and the degrees being of the same magnitude as those on the Fahrenheit scale. Temperatures referred to this new scale are called

absolute temperatures, and its zero point (—460 degrees Fahrenheit) absolute zero. The Fahrenheit scale is converted to the absolute scale simply by adding 460 degrees to the Fahrenheit reading.

Since the volume of a gas at constant pressure varies as the absolute temperature, if one pound of gas is at a temperature of 60 degrees Fahrenheit and a second pound at 500 degrees Fahrenheit, the respective volumes at a given pressure would be in the ratio of 60+460=520 to 500+460=960.

In combustion work, gas analyses are frequently given in terms of volume when analyses in terms of weight are required. To convert a volumetric analysis to one by weight, the percentage by volume of each constituent gas should be multiplied by its relative density, each product being divided by the sum of the products. To convert an analysis by weight to one in terms of volume, the percentage by weight of each constituent should be divided by its relative density, and each quotient so obtained be divided by the sum of the quotients. Since the molecular weights of the various gases bear the same relations to each other as the relative densities, these molecular weights may be used in transforming analyses instead of the relative densities.

Another method of converting volumetric analyses to analyses in terms of percentage by weight is through the use of the weights per cubic foot of the various constituent gases. The percentages by volume are multiplied by the weights per cubic foot, and each product is divided by the sum of the products. This method has an advantage in that it gives directly, in the sum of the products, the weight of the gas as a whole per cubic foot.

HEAT OF COMBUSTION

WHEN elements enter into a direct combination to form a compound a definite amount of heat is either evolved or absorbed. Such amount of heat is called the heat of combination and from its very definition may be either positive or negative. When a compound is decomposed into its constituent elements the amount of heat absorbed or evolved is exactly the same as that which was evolved or absorbed in the original formation of the compound. When both combination and decomposition are involved in a complex chemical change the heat produced or absorbed is the net result of the two reactions.

Heat of Combustion

Since the term combustion, as used in furnace practise, is limited to the rapid chemical combination of the combustible constituents of a fuel and oxygen, with a resulting production of heat, the heat of combustion of a fuel is obviously the heat evolved in the complete oxidization of such combustible elements through union with oxygen. The heat of combustion is thus the heat of combination of a specific set of elements and compounds, the combination of which with oxygen always results in the production of heat. It follows that the heat of combination of a compound which results from the union of a single combustible element with oxygen to produce heat is the same as the heat of combustion of that element.

The principles controlling the development of heat by combustion as generally accepted as authoritative are those propounded by Berthelot. His "second law" is of particular interest in combustion as limited to furnace practise, and as applied to such practise may be stated as follows:

The heat energy evolved in any chemical change in the boiler furnace, where no mechanical work is done, *i. e.*, evolved through the union of combustible elements with oxygen, is dependent upon the final products of combustion and in no way upon any intermediate combination or combinations that may have occurred in reaching the final result.

The application of this law may be readily shown by example:

A coal fire from which all of the volatile constituents have been driven and which consists of incandescent coke may for

the present purpose be considered as consisting entirely of carbon. If air is introduced under the fire the oxygen immediately breaks its mechanical union with nitrogen and enters into chemical combination with carbon to form carbon dioxide ($C+2\,O=CO_2$). Each unit of carbon has combined with the maximum amount of oxygen with which it can exist as a compound. The oxygen on the other hand is capable of uniting with additional carbon and as the unit of carbon dioxide passes upward through the fuel bed under the influence of draft it encounters other free carbon with which it unites to form carbon monoxide ($CO_2+C=2CO$), thus "satisfying the affinity of oxygen for carbon." If no additional oxygen is encountered in the further passage through the fuel bed, these particular molecules, as representative of the products of combustion, will issue from the fuel bed as carbon monoxide. If no additional oxygen is encountered in the furnace the total heat available for later absorption by the boiler is that due to the combustion of carbon to carbon monoxide regardless of the fact that at one stage of the process the carbon had been completely oxidized and carbon dioxide had been produced. If, on the other hand, additional oxygen is encountered in the furnace, the temperature is above the ignition point of carbon monoxide, and this temperature is maintained a sufficient length of time for further combustion, *i. e.*, if the gases are not cooled below the ignition temperature by the boiler heating surface before further combustion can be completed, the carbon of the carbon monoxide will unite with additional oxygen to form carbon dioxide ($2CO+2\,O=2CO_2$). The total heat evolved and available for absorption in such cases will be that due to the burning of carbon to carbon dioxide regardless of the two intermediate steps.

That combustible substances exist is, under the laws of chemical combination, an absolute indication that at some time there was expended an amount of energy in some transformable shape equivalent to the heat of combustion of the individual substance considered. While it is not within the province of the present article to discuss the reactions which brought about the state of existence of the combustible substances as used for commercial heat generation, the above statement may be accepted as true and the principles involved simply

as being of the general laws covering the conservation of energy. The heat of combustion of a fuel, or as it is sometimes called, the calorific value, as used in boiler practise, is the amount of heat expressed in B. t. u. generated by the complete combustion or oxidization of one pound of the fuel in question. The amount of heat so generated is a constant for any given combination of combustible elements and compounds, and in accordance with Berthelot's second law is irrespective of the manner in which combustion takes place, so long as it is complete.

The unit of measure of *quantity* of heat is, as stated above, the B. t. u. Until recently this has ordinarily been defined as the amount of heat necessary to raise the temperature of one pound of water at a definite temperature, one degree Fahrenheit. The value as now generally accepted is $\frac{1}{180}$th of the amount of heat necessary to raise the temperature of one pound of water from 32 degrees to 212 degrees Fahrenheit.

Table 6 gives the heat of combustion of what may be termed the "pure fuels" whether elements or compounds. These are found in various combinations in the fuels encountered in boiler practise.

TABLE 6*
HEAT OF COMBUSTION
BY CALORIMETRIC DETERMINATION

Combustible	Molecular Symbol	Heat Value—B. t. u. per Pound		Per Cubic Foot‡
		Higher	Lower or Net†	Higher
Hydrogen. . . .	H_2	62000	52920	348
Carbon (to CO) . .	C	4380	. . .	. . .
Carbon (to CO_2) .	C	14540	. . .	. . .
Carbon Monoxide .	CO	4380	. . .	342
Carbon in CO§ . .	C	10160	. . .	. . .
Methane	CH_4	23850	21670	1073
Acetylene. . . .	C_2H_2	21460	21020	1590
Ethylene	C_2H_4	21450	20420	1675
Ethane	C_2H_6	22230	20500	1883
Sulphur (to SO_2) .	S_2	4050	. . .	. . .
Sulphur (to SO_3) .	S_2	5940	. . .	. . .

† There is a considerable discrepancy between lower heat values as given by different authorities, the variation being due to methods of computation and assumptions. (See text.) The values given are those of G. A. Goodenough.

‡ At 32 degrees Fahrenheit and atmospheric pressure.

§ Per pound of carbon in carbon monoxide, *i. e.*, 2.33 pounds of CO.

* Heating Value by Calorimetry, see Discussion, page 23.

It appears from Table 6 that when one pound of carbon is burned to carbon monoxide the heat produced is 10,160 B. t. u. less than if the carbon were completely oxidized or burned to carbon dioxide. That such a difference exists in the amount of heat evolved in the burning of a fuel in two different ways offers the possible source of one of the most prolific of furnace losses. This will be discussed at greater length in connection with air supply and combustion.

The heat of combustion of a fuel is the basis upon which the efficiency of a steam boiler is computed and is therefore of the greatest importance.

Measurement of Heat of Combustion

The most satisfactory method of determining the heat value of any fuel is by the direct measurement of the heat evolved during combustion in a calorimeter. Descriptions of fuel calorimeters and the methods of their operation are given by numerous authorities and need no discussion here.

For solid fuels and most liquid fuels, calorimeters of the "bomb" type in which combustible substances are burned in a constant volume of oxygen, give the most satisfactory results. With such calorimeters, properly operated, combustion will be complete, all of the heat generated will be absorbed and measured, and heat from external sources can either be excluded or have proper correction made for its presence.

For gaseous fuels calorimeters of the continuous or constant flow type are ordinarily used, the Junker calorimeter being accepted as standard for this class of work.

The accuracy of the determination of the heat value of a fuel by calorimetry is largely a question of the personal equation; the more careful the manipulation of the instrument the more accurate will be the results. With careful manipulation, the results should be accurate to within a fraction of one per cent.

For solid and liquid fuels separate determinations are necessary for the heat value of each specific fuel. For elements and combustible compounds entering into gaseous fuels the heats of combustion have been determined by so many authorities that definite values may be accepted as correct without determination. In view of the difficulties of computing the heat values of such combustibles this fact is fortunate.

While the heat value of a fuel may, as stated, be most satisfactorily determined by actual experiment in a calorimeter, it frequently happens that such apparatus is not available. Under such conditions approximate heat values may be determined for certain fuels by computation from the ultimate chemical analysis of the fuel. The formula for such computation in most general use and which for most coals gives reasonably accurate results is that of Dulong. This formula, using approximate figures, is

$$\text{B.t.u. per pound} = 14{,}600\ C + 62{,}000\ \left(H - \frac{O}{8}\right) + 4050\ S \quad (4)$$

the symbols representing the proportionate parts by weight of carbon, hydrogen, oxygen and sulphur in the fuel, while the coefficients represent the approximate heating values of the constituents with which they appear in the formula. The term $\left(H - \frac{O}{8}\right)$ is assumed to contain a correction for the hydrogen in the fuel which is combined with oxygen and exists as moisture.

Dulong's formula will give as stated, very close approximations for the heat value of most coals—probably within 2 or 3 per cent. There are, however, certain sources of possible error in the use of the formula even for the fuels with which it gives the most accurate results, and since these sources of error offer the explanation of why the formula is not applicable to all fuels, and particularly to gaseous fuels, their discussion seems warranted.

(*a*) Carbon and sulphur are the only elements in coal in a free state, and but a portion of these constituents may occur in elementary form. The carbon may be present as graphite or as amorphous carbon, the heating values of which are entirely different. The sulphur may exist as FeS_2 (pyrites). Further, the sulphur may be burned to SO_2 or SO_3, in the production of which the amount of heat evolved is widely different. (See Table 6.)

(*b*) If a portion of the carbon and hydrogen are combined as hydrocarbons, the heating value of such combinations are far different than if the elements existed separately, since in such case the heat of combination or of dissociation would have to be

considered. This factor makes questionable the heat value of a portion of the carbon and probably of all of the hydrogen.

(*c*) The term $(H-\frac{O}{8})$ which is assumed to be correct for that portion of hydrogen contained in the moisture is not a proper assumption since a portion of the oxygen unquestionably exists in a free state in all fuels.

(*d*) An additional portion of the oxygen is in all probability combined with nitrogen in certain organic nitrates and some may possibly exist in combination as carbonates in mineral matter foreign to the coal.

All of these factors tend toward error. While with most coals the error is small, it is unfortunately, with the generally accepted co-efficients, one of excess. In the case of gaseous fuels, however, in view particularly of items (*b*) and (*c*) above, the chance of error is great. The magnitude of error will depend in such cases upon the individual set of hydrocarbons present in the fuel. If we had for instance a fuel composed of $C_5H_6O_2$, the constituents might be united in such a number of different combinations as to give results varying with the manner of combination, from 2.3 per cent less to 14.7 per cent greater than the result which would be obtained from the application of Dulong's formula, which assumes that all of the oxygen is combined with hydrogen as water.

Numerous other formulae of an empirical nature for the determination of the heat value of fuels have been offered by various authorities. Most of these are based upon a series of chemical analyses, and while they give reasonably accurate results in the case of individual classes of coal, they fail when an attempt is made to apply them not only to other classes of fuel, but even to other classes of coal.

The only accurate and reliable heating value of a fuel is that determined experimentally with a calorimeter, and such determination should correctly be reported as a part of the ultimate or proximate chemical analysis of the fuel.

In the case of commercial gases where the proportionate parts by weight may be readily determined, the heating value may be accurately computed from a table of the heat values of individual constituents, which values have been definitely fixed by numerous calorimetric experiments.

Higher and Lower Heat Values

The heat value of a fuel as defined is known as the "higher" heat value and is ordinarily accepted as the standard in this country. In the case of fuel containing hydrogen, and this includes practically all fuels in commercial use, there is another value known as the "lower", "net" or "available" heat value, in the determination of which an attempt is made to allow for the latent heat recovered in the condensation of the water vapor formed in the combustion of hydrogen. For example: In the calorimetric determination of the heat value of a fuel containing hydrogen, the products of combustion are cooled to approximately the temperature of the original mixture, say 62 degrees Fahrenheit. In cooling the products to this temperature the water vapor formed by the combustion of hydrogen is condensed, and the result, expressed in B. t. u., after being corrected for sulphur and like factors, *i. e.*, the higher heat value, includes the latent heat of water vapor given up in such condensation.

If the lower value be represented by H_p' and the weight of water produced per pound of fuel by w, the lower heat value may be determined from

$$H_p' = H_p - wr \qquad (5)$$

where H_p equals the higher heat value and r is a factor which varies with the percentage of hydrogen in the fuel, the amount of air or oxygen used in combustion, the moisture in the air and the temperature to which the products of combustion are cooled in the calorimeter. Too frequently r is simply taken as the latent heat of steam either at 32 degrees or 212 degrees, though in calorimetric work neither of these temperatures are apt to occur.

With the lower heat value so defined, the difference between the higher and the net value will obviously be the total heat of the steam or water vapor as it escapes less the sensible heat of an equivalent weight of water at the temperature of the fuel and of the oxygen before combustion takes place.

The lower heat value is in common use in Great Britain and in most foreign countries. In this country the higher value is almost universally accepted, and this is the standard recommended by the American Society of Mechanical Engineers.

Any attempt to make use of the lower heat value introduces a source of possible error in the proper temperature for use in

computation, and advocates of the use of this value are not in entire agreement as to the proper methods of such computations.

To sum up, a theoretically perfect absorption of heat after combustion would condense all of the moisture formed in the burning of hydrogen, and since the efficiency of any apparatus is based upon the performance of a theoretically perfect machine, it appears only logical to charge against the apparatus what would be secured from the theoretically perfect. Further, in the report of the performance of any apparatus, a heat balance offers a method of determining and expressing any loss due to the burning of hydrogen, and no such test or performance report can be accepted as reliable unless accompanied by a heat balance or by data from which a heat balance may be computed.

SPECIFIC HEAT

THE heat of combustion of any substance from its very nature must have an important bearing on the temperature which will result from the burning of such substance. Before discussing the temperatures so developed, a knowledge of the specific heats is necessary. This subject is important in the computation of much combustion data, and for this reason is considered at length.

The specific heat of a substance is the amount of heat expressed in thermal units required to raise unit weight of the substance through one degree of temperature, the units in this country being one pound and one degree Fahrenheit.

The specific heat of all substances varies with the temperature. Since all substances vary in volume or in pressure with changes in temperature, it is necessary to distinguish between the specific heats at constant volume and at constant pressure, expressed ordinarily as C_v and C_p, respectively.

Liquids and solids, because of their low co-efficients of expansion, vary but little in volume under a temperature change of one degree and for these substances therefore there is but little difference in the specific heat at constant volume and that at constant pressure. With gases, on the other hand, there is a decided distinction. When any heat is added to a gaseous substance, its volume may be kept constant, in which case no external work is done, or the gas may be allowed to expand during the addition of heat, the pressure being kept constant. The specific heat at constant volume therefore will always be less than that at constant pressure by the amount of heat required to do the work of expansion against external pressure.

Under both specific heat at constant pressure and that at constant volume it is necessary to distinguish still further between *instantaneous* and *mean* specific heat.

The instantaneous specific heat of a substance is the amount of heat that must be added to a unit weight of such substance at some definite temperature to increase its temperature one degree, under given conditions of pressure or volume.

The mean specific heat of a substance, over a given temperature range, is the value by which such range must be multiplied

to determine the quantity of heat necessary to raise unit weight of the substance through the range under the conditions of pressure or volume which exist.

In the computation of combustion data the mean specific heat should be used.

From the definition of a B. t. u. as hitherto accepted (see page 22), when the specific heat of water is given as unity, such value would express the instantaneous specific heat at constant pressure, at the standard temperature (usually 62 degrees Fahrenheit). From the definition now accepted—namely, $\frac{1}{180}$th of the heat required to raise one pound of water from 32 degrees to 212 degrees Fahrenheit—where the specific heat is given as one, such value is the mean specific heat between 32 and 212 degrees.

Except in the case of water vapor, the variation with pressure in the specific heat of the gases ordinarily encountered in combustion work is negligible. In the case of water vapor, where it is necessary to deal with any considerable range of pressures, this variation would be an appreciable factor, but in the commercial gases involved in combustion, the partial pressure exerted by water vapor, either in gases before combustion or in the exhaust gases is rarely over one pound absolute. With such a limited pressure range and in view of the fact that the water vapor content of the gases is small, the effect of such variation in pressure on the specific heat of the gas as a whole may be neglected.

The range of pressure in the gases encountered in boiler work is so limited—varying from that at which the commercial gases are introduced into the furnace for combustion to the suction under which they are drawn over the boiler heating surfaces—that in the computation of combustion data the gases may be safely assumed to be at a constant pressure. The specific heat at constant pressure is the specific heat which should be used, and any results based on the assumption of a constant pressure of the gases as a whole, and in which the variation in the specific heat of the water vapor content with change of pressure is neglected, will be well within the limits of accuracy of practically all combustion data computation.

While the variation in specific heat with pressure can be neglected, the variation with temperature is a very appreciable

factor and must be given proper consideration where accuracy is desired.

The results of the great amount of experimental work that has been done in the determination of the specific heat of gases are unfortunately not in complete agreement. From the work of Holborn and Henning, Langen, Pier and Austin, however, the specific heats of the diatomic gases (H_2, O_2, N_2 and CO) and of carbon dioxide and water vapor are pretty definitely determined. The values for these gases which follow are apparently the most authoritative of those that have been offered.

The general formula for the specific heat of a gas at constant pressure may be expressed by the function

$$c_p = a + bt + ct^2 + dt^3 \qquad (6)$$

The mean specific heat of a gas between the temperatures t_1 and t_2 will be then

$$c_p = \int_{t_1}^{t_2} \frac{a + bt + ct^2 + dt^3}{t_2 - t_1} - dt$$

or by integration

$$c_p = a + \frac{b}{2}(t_2 + t_1) + \frac{c}{3}[(t_2 + t_1)^2 - t_2 t_1] + \frac{d}{4}$$

$$[(t_2 + t_1)(t_2 + t_1)^2 - 2t_2 t_1] \qquad (7)$$

Carbon Dioxide

The value of the instantaneous specific heat at constant pressure of CO_2, as given by Holborn and Henning, in terms of the Fahrenheit scale is

$$c_{p_t} = 0.1983 + 835 \times 10^{-7} t - 16.7 \times 10^{-9} t^2 \qquad (8)$$

Values as determined by this formula decrease rapidly at temperatures above 2400 degrees Fahrenheit. That such a decrease occurs appears questionable, and for this reason it seems advisable to modify the formula in such a manner as to continue the increase in specific heat with temperature in a logical way. Mathias Pier investigated the specific heat of CO_2 at high temperatures and the values as determined by him are above those of Holborn and Henning. A modification of Holborn

and Henning's formula (*8*) for use in the case of temperatures above 2200 degrees D. which appears to give logical results is

$$c_{p_t} = .1991 + 873 \times 10^{-7} t - 23.4 \times 10^{-9} t^2 + 0.22 \times 10^{-11} t^3 \quad (9)^*$$

This formula gives values for the specific heat of CO_2 above 2200 degrees Fahrenheit greater than those of Holborn and Henning and somewhat less than those of Pier.

Formula (*8*), which should be used for temperatures up to 2200 degrees Fahrenheit, in terms of mean specific heat at constant pressure for a temperature range *o*—*t*, in accordance with the relation between instantaneous and mean specific heats as indicated by formulae (*6*) and (*7*) will become

$$c_{p_{o-t}} = 0.1983 + 417.5 \times 10^{-7} t - 5.567 \times 10^{-9} t^2 \quad (10)$$

For a range of definite temperatures, t_1—t_2, the constants will be the same as in (*10*), the values of t_1 and t_2 being substituted as indicated in (*7*).

For temperatures above 2200 degrees, the mean specific heat at constant pressure between *o* and *t* degrees Fahrenheit becomes from formula (*9*)

$$c_{p_{o-t}} = 0.1991 + 436.5 \times 10^{-7} t - 7.8 \times 10^{-9} t^2 + 5.5 \times 10^{-13} t^3 \quad (11)$$

and for a temperature range t_1—t_2, the proper value may be computed in accordance with values of t_1 and t_2 indicated by (*7*), using the constants as given in (*11*).

Carbon Monoxide and Nitrogen

Holborn and Henning give the instantaneous specific heat of nitrogen at constant pressure as

$$c_{p_t} = 0.2343 + .000021\ t \quad (12)$$

Their investigations extended to a temperature of 2456 degrees Fahrenheit and appear to offer the most authoritative values. In the absence of data at higher temperatures it is necessary to accept this formula for all temperatures.

The mean specific heat between *o* and *t* becomes then

$$c_{p_{o-t}} = 0.2343 + .0000105\ t \quad (13)$$

and for a range t_1—t_2 as indicated in the case of carbon dioxide.

Formulae (*12*) and (*13*) will also give the specific heat of carbon monoxide.

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* See "Experiments on the Rate of Heat Transfer from a Hot Gas to a Cooler Metallic Surface." The Babcock & Wilcox Co., 1916.

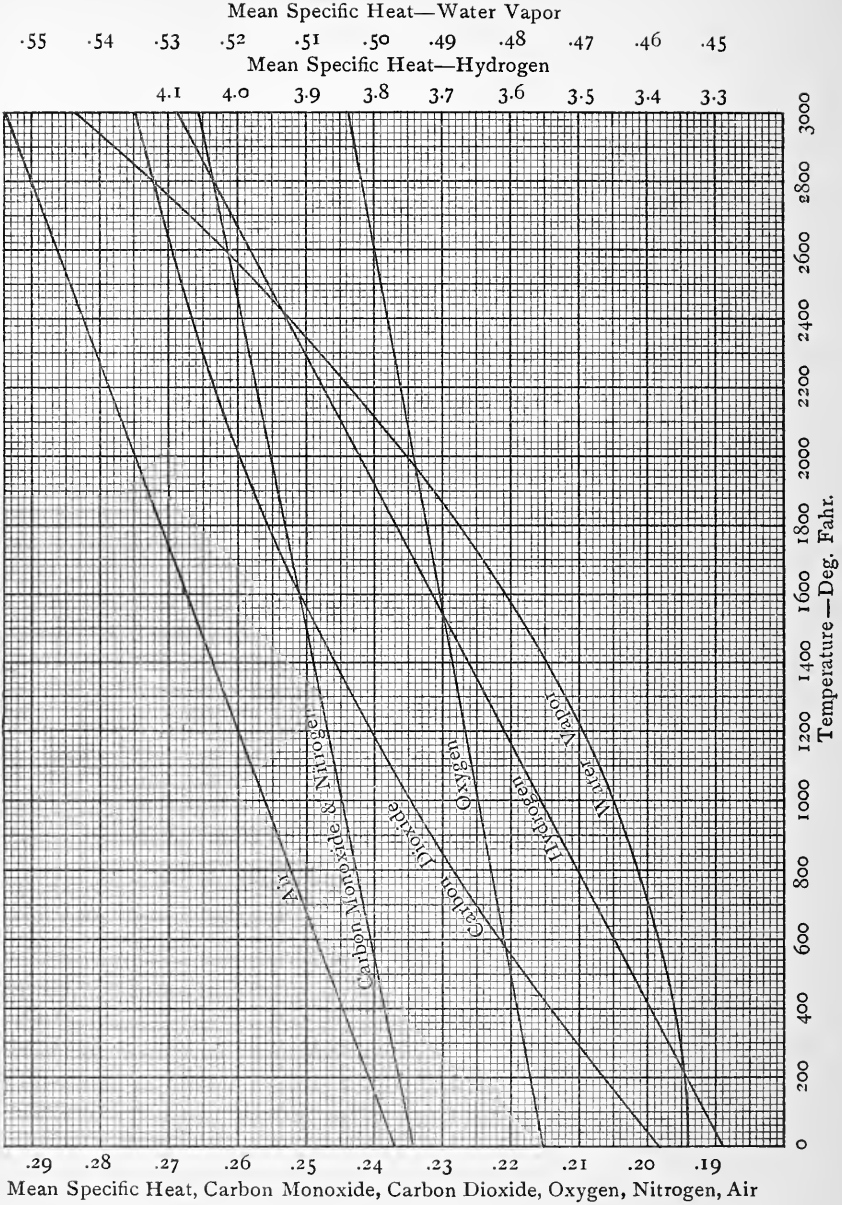
Mean Specific Heat—Water Vapor
·55 ·54 ·53 ·52 ·51 ·50 ·49 ·48 ·47 ·46 ·45
Mean Specific Heat—Hydrogen
4.1 4.0 3.9 3.8 3.7 3.6 3.5 3.4 3.3
Water Vapor
Hydrogen
Oxygen
Carbon Dioxide
Nitrogen
Carbon Monoxide
Air
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000
Temperature—Deg. Faht.
.29 .28 .27 .26 .25 .24 .23 .22 .21 .20 .19
Mean Specific Heat, Carbon Monoxide, Carbon Dioxide, Oxygen, Nitrogen, Air

FIGURE 1

Oxygen

The data on the specific heat of oxygen is meagre. Holborn and Austin experimented with oxygen mixed with 9 per cent nitrogen up to temperatures of 1160 degrees Fahrenheit, while Langen and Pier investigated at higher temperatures. The best formula offered * is apparently one which gives values somewhat higher than those of Langen and Pier, but which agrees more nearly in values with that proposed by Holborn and Henning.

This formula for the instantaneous specific heat or oxygen at constant pressure is

$$c_{p_t} = 0.2154 + 0.000019\ t \qquad (14)$$

and for the mean specific heat over the range o—t

$$c_{p_{o-t}} = 0.2154 + .0000095\ t \qquad (15)$$

Hydrogen

Holborn and Henning give as the mean molecular specific heat of hydrogen

$$mc_{p_{o-t}} = 6.58 + 0.000532\ t \qquad (16)$$

This in terms of mean specific heat becomes

$$c_{p_{o-t}} = 3.29 + 0.000266\ t \qquad (17)$$

Water Vapor

The formula for the specific heat of water vapor is based on the values given in Marks and Davis' Steam Tables. This formula for the instantaneous specific heat at a constant pressure of one pound absolute (which may be accepted as correct for the partial pressure of the water vapor in the gases of combustion data work over the range of draft pressure or suction found) is

$$c_{p_t} = 0.4541 + 32 \times 10^{-7} t + 2825 \times 10^{-11} t^2 \qquad (18)^*$$

The mean specific heat for the range o—t will be

$$c_{p_{o-t}} = 0.4541 + 16 \times 10^{-7} t + 942 \times 10^{-11} t^2 \qquad (19)$$

For a range of temperature t_1—t_2 this means specific heat will be

$$c_{p_{t_1-t_2}} = 0.4541 + 16 \times 10^{-7} (t_2 + t_1) + 942 \times 10^{-11} [(t_2 + t_1)^2 - t_2 t_1] \qquad (20)$$

* See "Experiments on the Rate of Heat Transfer from a Hot Gas to a Cooler Metallic Surface." The Babcock & Wilcox Co., 1916.

The specific heat of a gaseous mixture is found by multiplying the percentage by weight of each of the constituent gases by the specific heat of that gas and dividing the sum of the products by 100.

Investigations of the specific heats of other important gases encountered in combustion work, over any considerable temperature range are lacking, though it is possible in one or two instances, to give formulae from which approximate values may be computed. In the computation of combustion work such gases (CH_4, C_2H_4, etc.) are ordinarily dealt with at atmospheric or at least at low temperatures, under which conditions reasonably accurate values are available. Further, the percentages of such gases in the ordinary gaseous fuels is not such as to cause any great error in the determination of the specific heat of the gas as a whole through the use of inaccurate or questionable specific heats for these individual constituents. What appear to be the most authoritative values for the specific heats of these gases at 60 and 600 degrees are given in Table 7.

TABLE 7

MEAN SPECIFIC HEATS AT CONSTANT PRESSURE AND ORDINARY TEMPERATURES

	Molecular Symbol	Mean Specific Heat	
		0—60 Degrees Fahrenheit	0—600 Degrees Fahrenheit
Air	. . .	.2381	.2484
Oxygen	O_2	.2160	.2211
Hydrogen	H_2	3.3850	3.4750
Nitrogen	N_2	.2349	.2406
Carbon Monoxide	CO	.2349	.2406
Carbon Dioxide	CO_2	.2008	.2214
Water Vapor	H_2O	.4542	.4586
Methane*	CH_4	.498	.649
Ethylene†	C_2H_4	.348	.461
Sulphur Dioxide	SO_2	.1544	. . .

* Methane—$C_{p_{o-t}}=0.481+0.00028\ t$

† Ethylene—$C_{p_{o-t}}=0.335+0.00021\ t$

The mean specific heats between o and t the gas temperature of the ordinary gases encountered in combustion work, and of water vapor are shown graphically in Figure 1.

TEMPERATURES DEVELOPED IN COMBUSTION

IF in the burning of any fuel, it is assumed

First, that combustion is complete;

Second, that there is no radiation loss;

Third, that there is no dissociation; and

Fourth, that the inert gases play no part in the reaction, the total heat generated must be transferred to the products of combustion, and raise their temperature above that of the fuel and the air supplied for combustion a definite amount, depending upon the constituents of the fuel.

Under such assumptions, the theoretical elevation in temperature, from which the temperature developed by the combustion of any fuel can be determined may be expressed

$$T=\frac{\text{B. t. u. produced}}{W \times c} \qquad (21)$$

where T=elevation in temperature,

W=weight of products of combustion,

c=mean specific heat of products between temperature of fuel and air and that of products.

Since, as has been shown, the value of c in (21) will vary over a considerable range with temperature, this expression cannot be used for a direct temperature computation. It is possible, however, to compute the theoretical temperature resulting from the combustion of a given fuel under given conditions by the use of a method involving trial and error as follows:

Assuming the conditions as given above, the heat energy of a fuel mixture above o degrees Fahrenheit, plus the amount of heat generated, must equal the heat energy of the products of combustion above o degrees Fahrenheit. If M equals the sum of the fuel constituents ($m^1+m^2+m^3+\ \ $) and M^1 the sum of the constituents of the products of combustion ($m_1+m_2+m_3+\ \ $)

the formula for the determination of the theoretical temperature developed may be expressed

$$Mc_p t_1 + \text{Heat generated}^* = M^1 c_p{}^1 t_2 \qquad (22)$$

where t_1 = temperature of fuel mixture,

t_2 = temperature evolved in combustion,

c_p and c_p^1 = mean specific heats of fuel mixture and products of combustion, respectively.

Since t_2 is unknown, c_p^1 is also unknown, and, as stated, the method of trial and error must be used. This method is best illustrated by example, and is perhaps most fully indicated by the consideration of a gaseous fuel. Assume then, blast furnace gas having an analysis as follows:

	By Volume Per Cent	By Weight Per Cent
CO	27.36	26.65
H_2	3.16	.23
CH_4	.53	.30
CO_2	10.00	15.40
N_2	58.95	57.42

If this gas is burned with 20 per cent excess air the products of combustion from Table 8 will be

	Weight per Pound Gas Burned	Theoretical Amount Pounds		Products of Combustion Pounds			
		O_2	Air	CO_2	N_2	H_2O	O_2
CO	.2665	.1519	.6556	.4184	.5037	. . .	. . .
H_2	.0023	.0184	.0795	. . .	.0611	.0207	. . .
CH_4	.0030	.0120	.0518	.0083	.0398	.0068	. . .
CO_2	.1540	. . .	. . .	.1540	. . .	. . .	. . .
N_2	.5742	. . .	. . .	. . .	.5742	. . .	. . .
			.7869	. . .	. . .	. . .	. . .
20 per cent excess . . .			.1574	. . .	.1210	. . .	.0364
Total Products				.5807	1.2998	.0275	.0364

*It is to be noted in the case of fuels containing hydrogenous constituents, since no condensation of water vapor occurs, the lower or available heat value of such constituents is the proper value for use in the computations. These values may be taken from Table 6

If the temperature of the fuel mixture before combustion is 250 degrees Fahrenheit, the computations involved in the use of formula (*22*) under the assumed conditions, expressed in tabular form are:

	Composition of Fuel Mixture M	Lower Heat Value H_v	M. H_v	Mean Specific Heat $c_{p_{o-250}}$	M. $c_{p_{o-250}}$
CO	.2665	4380	1167	.2369	.063134
H_2	.0023	52900	122	3.3665	.007743
CH_4	.0030	21670	65	.5510	.001653
CO_2	.1540	. . .	. . .	.2084	.032094
O_2	.0364*	. . .	. . .	.2178	.007928
N_2	.6952†	. . .	. . .	.2369	.164693
	. . .	. . .	1354	. . .	.277245

*From 20 per cent excess air. †Includes N_2 from excess air.

The heat energy of the fuel mixture above 0 degrees will be then

$$M.\, c_{p_{o-250}}\ .t_1 = .277245 \times 250 = 69.31 \text{ B. t. u.}$$

Since t_2 is unknown it is necessary to assume a trial value in order to compute $c_{p_{o-t_2}}$. With $c_{p_{o-t_2}}$ computed for such trial value, formula (*22*) may be solved for t_2 and the value of t_2 so determined used for a second trial.

If then we assume t_2, the theoretical temperature evolved under the conditions of combustion given as 3000 degrees Fahrenheit, we have

	Products—M^1	$c_{p_{o-3000}}$	M^1. $c_{p_{o-3000}}$
CO_2	.5807	.2747	.159518
O_2	.0364	.2439	.008878
H_2O	.0275	.5437	.014952
N_2	1.2998	.2658	.345487
			.528835

Substituting in formula (*22*)

$$69.31 + 1354 = .528835\ t_2$$

$$t_2 = 2710 \text{ degrees}$$

Using as a second trial value $t_2 = 2750$ degrees, we have

	Products—M[1]	$C_{p_{0-2750}}$	M[1]. $C_{p_{0-2750}}$
CO_2	.5807	.2715	.157660
O_2	.0364	.2415	.008790
H_2O	.0275	.5297	.014567
N_2	1.2998	.2632	.342107
			.523124

Substituting again in formula (*22*)

$$69.31 + 1354 = .523124\ t_2$$

$$t_2 = 2721 \text{ degrees}$$

The theoretical temperature evolved under the assumed conditions will thus be approximately 2735 degrees Fahrenheit. The above method may be continued if more accurate results are desired.

In the consideration of the theoretical temperature it is evident that the time element, *i. e.*, the length of time necessary to complete combustion, does not enter, though in actual practise this is an appreciable factor.

In practise, the temperature which, for a given fuel, is theoretically possible, is never obtained. The main factor in the burning of ordinary fuels which results in a temperature below that theoretically possible, is the dilution of the products of combustion through the introduction of a greater amount of air than is required for complete oxidization, *i. e.*, the presence of excess air. Under such conditions there are present in the products of combustion amounts of oxygen and nitrogen in excess of the amounts required for combustion, which excess weights must be heated from the temperature at which they are introduced to the ultimate temperature of the gases. In using a portion of the definite amount of heat that a given fuel will generate for so increasing the temperature of these excess weights of oxygen and nitrogen, the temperature of the ultimate mixture will be reduced to below that which would exist were there no excess gases to be heated.

Temperatures below the theoretical will also result from an insufficient air supply. Under such conditions there is a loss in the heat generated due to incomplete combustion of carbon (burning to CO instead of CO_2).

A further reduction below the theoretical temperature occurs through loss in radiation. While the time element does not enter into any computation involving formula (*22*), in practise, since the quantity of heat radiated from a given mass of fuel is a function of the time during which combustion takes place, it is obvious that a portion of the heat generated will be lost through radiation, such loss increasing as combustion is slower.

The two important reactions of combustion

$$2H_2+O_2=2H_2O \text{ and } 2CO+O_2=2CO_2$$

are reversible and if such dissociation occurs it would have a decided effect on the temperature developed in combustion. The amount of dissociation which takes place under the temperatures developed in boiler furnace practise is not definitely known but is probably inappreciable. For commercial combustion this factor may be considered as negligible.

From the factors involved it is evident that the better the combustion, *i.e.*, the more complete with the minimum of excess air, the higher the temperature developed, and it follows that the better the combustion and the higher the temperature, again assuming the ability of the boiler to efficiently absorb heat, the better the efficiency. It is very difficult with the means available to determine accurately the actual temperature developed in commercial combustion, and hence to make use of such temperature as a measure of the efficiency of combustion. Fortunately there are other methods by which such efficiency may be determined with a considerable degree of accuracy.

Flame

The appearance of combustion, *i. e.*, the "look" of the mass of fuel and of the products of combustion, offer to the experienced eye a measure of the temperatures developed. While the use of such a method can lead only to the most approximate results, and at best serve simply as a check of more accurate determinations, it is perhaps worth while to consider it.

The physical evidence by which the temperature and the degree and the extent of combustion in a boiler furnace may be judged, is the appearance of the flame, the fuel itself being visible but rarely. Flame may be defined as a mass of intensely

heated gas in a state of combustion, though it is possible for flame to exist as gas not actually in such state. The luminosity of flame, or the characteristic which gives its visibility, is due to the heating to incandescence of the unconsumed particles of combustible matter present in the gases, and the variation in the colors of flame is due to the difference in the degree of heat communicated to these particles. The higher the temperature of these particles the whiter the flame. The length and volume of the flame will vary with the combustible elements present, and the thoroughness with which the air and combustible elements are mingled, and since such number will decrease with an increase in the completeness of combustion, the shorter the flame, in the absence of any outside cooling medium, the more rapid and complete the combustion.

If it were possible for the combustion of any fuel to be complete and instantaneous there would be no visible flame, since both carbon dioxide and water vapor are invisible. Visible flame, then, is evidence of incomplete or non-combustion, but such evidence in the commercial furnace means simply that the combustion has not taken place with sufficient rapidity to evolve heat instantaneously.

It follows from the above that for a given amount of fuel burned, a short flame will ordinarily mean rapid and complete combustion, a longer flame delayed combustion, and a very long flame imperfect or non-combustion.

TABLE 7A

TEMPERATURE AND APPEARANCE OF FLAME*

Appearance of Flame	Temperature Degrees Fahrenheit
Dark Red	975
Dull Red	1290
Dull Cherry Red	1470
Full Cherry Red	1650
Clear Cherry Red	1830
Deep Orange	2010
White	2370
Bright White	2550
Dazzling White	2730

*Jos. W. Hays.

The temperature evolved in combustion may be approximated from the appearance of the fuel mass or the flame in accordance with the preceding table. Such figures are of necessity but the roughest approximations, but, in connection with the flame length, are of some value where apparatus for more accurate determination of the extent and degree of combustion is not available.

AIR AND COMBUSTION

THUS far, in the abstract consideration of combustion, the presence of sufficient oxygen for combination with oxidizable substances, and of a temperature sufficient to bring about the chemical combinations of combustion, have simply been assumed. As a matter of fact, given proper temperature conditions, it is the physical introduction of oxygen into the presence of combustible substances in such manner as to assure complete oxidization, and at the same time to assure the utilization of all or of the maximum proportion so supplied, that is the most important and difficult problem in the burning of all fuels.

The source of supply of the oxygen necessary for combustion is, as stated, the air. From the proportionate parts by weight of oxygen and nitrogen as given, namely, $O_2=23.15$ per cent and $N_2=76.85$ per cent, it is obvious that to supply one pound of oxygen for combustion it will be necessary to supply

$$1\div.2315=4.320$$

pounds of air, and that in this weight of air there will be 3.32 pounds of nitrogen which serves no useful function in combustion.

We have seen in Table 2, the chemical combinations occurring in the union of oxygen with the combustible elements and compounds found in the fuels used for the commercial generation of heat. From the manner of such combinations and dissociations, and a consideration of the atomic weights of the elements involved, the proportionate part by weight of the elements entering into the resulting compounds may be readily computed as well as the weights of the products of combustion. With the amount of oxygen required for combustion thus known the amount of air required will be indicated from the oxygen—nitrogen ratio existing in air.

The methods of such computations are clearly indicated by example, and since the relation of the products of combustion to the combustible elements of the fuel is the most important factor in the determination of the efficiency of combustion, it appears advisable to illustrate such computations fully.

Consider first carbon:

From Table 2 it was seen that one atom of carbon united with two atoms of oxygen to form carbon dioxide

$$C+2\,O=CO_2$$

From the atomic weights

$$12+(2\times 16)=44$$

or in the burning of one pound of carbon to carbon dioxide, twelve parts by weight of carbon combine with thirty-two parts by weight of oxygen to form forty-four parts by weight of carbon dioxide. Hence, any weight of carbon dioxide must be composed of 27.27 per cent by weight of carbon and 72.73 per cent by weight of oxygen, or

$$1 \text{ pound } CO_2=.2727 \text{ pounds } C+.7273 \text{ pounds } O_2$$

Since the ratio of carbon to oxygen in carbon dioxide is 1 to 2.667, it is obvious that in burning one pound of carbon to carbon dioxide, 2.667 pounds of oxygen will be required.

If one pound of oxygen is contained in 4.32 pounds of air it will be necessary to supply for the complete combustion of one pound of carbon

$$2.667\times 4.32=11.52$$

pounds of air, and since each pound of oxygen is accompanied by 3.32 pounds of nitrogen, there will pass off with the carbon dioxide

$$2.667\times 3.32=8.85$$

pounds of nitrogen.

In the complete combustion of one pound of carbon then the resulting products of combustion will be

$$1 \text{ pound } C+2.667 \text{ pounds } O_2=3.667 \text{ pounds } CO_2$$
$$2.667\times 3.32 \text{ pounds } N_2=8.885 \text{ pounds } N_2$$

Again, consider hydrogen:

Table 2 indicates that two atoms of hydrogen will combine with one atom of oxygen to form water vapor

$$2H+O=H_2O$$

From the atomic weights

$$(2\times 1)+16=18$$

or in the burning of one pound of hydrogen to water vapor, one part by weight of hydrogen will combine with eight parts by

weight of oxygen to form eighteen parts by weight of water vapor. Hence in one pound of water vapor we have

$$1 \text{ pound } H_2O = .111 \text{ pounds } H_2 + .889 \text{ pounds } O_2$$

Since the ratio of hydrogen to oxygen in water vapor is thus 1 to 8 it will require 8 pounds of oxygen for the complete combustion of one pound of hydrogen, which means, as for the combustion of carbon,

$$8 \times 4.32 + 34.56$$

pounds of air required to burn one pound of hydrogen.

The nitrogen present in this weight of air will be

$$8 \times 3.32 = 26.56 \text{ pounds } N_2$$

and the products of combustion of one pound of hydrogen will be

$$1 \text{ pound } H_2 + 8 \text{ pounds } O_2 = 9 \text{ pounds } H_2O$$
$$8 \times 3.32 = 26.56 \text{ pounds } N_2$$

As typical of the combustible compounds consider ethylene (the CH series are all computed in a similar manner)

$$C_2H_4 = 2C + 4H$$

or from atomic weights

$$28 = 24 + 4$$

Thus one pound of ethylene is composed of

$$.857 \text{ pounds } C + .143 \text{ pounds } H$$

To burn .857 pounds of carbon will require

$$.857 \times 2.667 = 2.2856 \text{ pounds } O_2$$

To burn .143 pounds of hydrogen will require

$$.143 \times 8 = 1.144 \text{ pounds } O_2$$

The total oxygen required then will be

$$2.286 + 1.144 = 3.430 \text{ pounds}$$

and the total air

$$3.43 \times 4.32 = 14.82 \text{ pounds}$$

The products of combustion will be

	CO_2 Pounds	H_2O Pounds	N_2 Pounds
.857 pounds C + 2.286 pounds O_2	= 3.143	. . .	. . .
.143 pounds H_2 + 1.144 pounds O_2	= . . .	1.287	. . .
14.82 pounds air x .7685 (per cent N in air)	= . . .	. . .	11.39

The methods of computation are simple but, as stated, are considered at length because of their importance, particularly in the case of gaseous fuels. Table 8 gives the results of such computations, in terms of weight, for all of the combustible elements and compounds encountered in commercial fuels. Table 9 gives such values in terms of volume.

TABLE 8

COMBUSTION DATA

IN TERMS OF POUNDS PER POUND OF FUEL

	Molecular Symbol	Theoretically Required Pounds		Products of Combustion Pounds				
		O_2	Air	CO_2	H_2O	N_2	CO	SO_2
Carbon (to CO_2)	C	2.667	11.52	3.667		8.85		
Carbon (to CO)	C	1.333	5.76			4.43	2.333	
Carbon Monoxide	CO	0.572	2.46	1.57		1.89		
Sulphur	S	1.000	4.32			3.32		2.00
Hydrogen	H_2	8.000	34.56		9.00	26.56		
Methane	CH_4	4.000	17.28	2.75	2.25	13.28		
Acetylene	C_2H_2	3.077	13.29	3.39	0.69	10.21		
Ethylene	C_2H_4	3.429	14.81	3.14	1.29	11.38		
Ethane	C_2H_6	3.733	16.13	2.93	1.80	12.40		
Hydrogen Sulphide	H_2S	1.412	6.10		0.53	4.69		1.88

TABLE 9

COMBUSTION DATA

IN TERMS OF CUBIC FEET PER CUBIC FOOT OF FUEL

	Molecular Symbol	Theoretically Required Cubic Feet		Products of Combustion Cubic Feet				
		O_2	Air	CO_2	H_2O	N_2	CO	SO_2
Carbon Monoxide	CO	0.5	2.391	1		1.891		
Hydrogen	H_2	0.5	2.391		1	1.891		
Methane	CH_4	2.0	9.564	1	2	7.564		
Acetylene	C_2H_2	2.5	11.955	2	1	9.455		
Ethylene	C_2H_4	3.0	14.346	2	2	11.346		
Ethane	C_2H_6	3.5	16.737	2	3	13.237		
Hydrogen Sulphide	H_2S	1.5	7.173		1	5.673		1

Considered from a chemical standpoint, the supplying of just the proper amount of oxygen or of air for perfect combustion, as

indicated by Table 8, appears simple. It is, however, the physical difficulty encountered in the introduction of just the proper amount of oxygen that is the main source of the losses occurring in the burning of any fuel.

It may be well to distinguish here between perfect and complete combustion. Perfect combustion, as shown in Table 8, is the result of supplying the requisite amount of oxygen for union with all of the oxidizable constituents of the fuel and utilizing in combustion all of the oxygen so supplied. Complete combustion on the other hand, results from the oxidization of all the combustible constituents of the fuel but does not of necessity imply the utilization of all of the oxygen supplied. If perfect combustion could be accomplished in a boiler furnace there would be no unavoidable combustion losses. While combustion is complete but not perfect, there are, as will be shown, losses due to the supplying of too great an amount of oxygen, and hence air, and it follows that the more nearly complete combustion can be made to approach perfect combustion, the less the loss that will occur in the burning of any fuel. It is in fact this problem—the seeking after perfect combustion—that is the problem of furnace design.

It is obvious from the foregoing that the real measure of the efficiency of combustion is to be found in the relations existing between the amount of air theoretically required for the burning of any fuel and the amount of air actually supplied for such combustion and before considering the possible furnace losses resulting either from incomplete combustion or from the supplying of too great an amount of oxygen it is necessary to understand the method of determining these relations.

The calculations involved in the determination of the weight of air required for the perfect combustion of a pound of a given fuel have been indicated in the computations of Table 8. For such determination an analysis of the fuel is necessary, this analysis in the case of solid and liquid fuels being given in terms of weight, and in the case of gaseous fuels either in terms of weight or of volume. While the analysis of gaseous fuels are ordinarily given in terms of volume, it is perhaps best to transform such analysis to a weight basis, since the results are usually desired in terms of weight.

With the data of Table 8 available, the development of formulae to give directly the theoretical amount of air necessary for the perfect combustion of any fuel is simple. Such formulae are given hereafter. There are, however, no suitable or reliable means of measuring or weighing the air actually admitted to a boiler furnace, and the only means of determining the amount of such air is from the analysis of the products of combustion—ordinarily called flue gases. In making use of such analysis certain assumptions, discussed hereafter, are necessary, but these assumptions are such that the results obtained from the proper consideration of a properly made analysis are well within the error of a boiler test as a whole.

The apparatus used in the determination of the constituents of flue gases and the methods of operating such apparatus have been too often described to need discussion here. In the ordinary commercial analysis the proportionate parts by volume of carbon dioxide, carbon monoxide and oxygen are determined, the difference between the sum of these constituents and 100 per cent being assumed as nitrogen.

Where combustion is complete, regardless of the amount of excess air, the only products of combustion that can result from the burning of any fuel are CO_2, SO_2 (or SO_3) H_2O and N_2. The ordinary commercial analysis then is in reality simply a measure of the completeness of combustion of the carbon content of a fuel. Properly used, however, such analysis may be made to give combustion data from which furnace losses may be computed within the required limits of accuracy.

It seems proper to emphasize here the necessity, where accurate results are desired, of considering flue gas analyses *only* in conjunction with analyses of the fuel burned. As an example of the errors that may arise where the two analyses are not considered together we may take the tables of preventable losses corresponding to varying percentages of carbon dioxide present in the flue gases, which are given in numerous publications. Such tables give an arbitrary percentage of carbon dioxide which, if it could be obtained would represent no preventable furnace loss, with increasing losses for lesser percentages of carbon dioxide.

For any fuel there will be a definite percentage of carbon dioxide that must correspond to perfect combustion and hence

to zero preventable loss, but such percentage will vary not only for different classes of fuels but even widely with different fuels of the same class. How wide this variation in carbon dioxide may be for perfect combustion with different fuels is indicated by the computations of combustion data given later, the range in the examples of fuel taken being from 9.4 per cent in the case of by-product coke oven gas to 25.1 per cent in the case of blast furnace gas. From these figures it is obvious that CO_2 tables are not to be accepted as a measure of preventable furnace loss, regardless of the class of fuel burned, and that for the intelligent use of a flue gas analysis, an analysis of the fuel burned is also essential.

COMBUSTION FORMULAE

AIR REQUIRED FOR COMBUSTION

WITH carbon, hydrogen, and sulphur the only combustible elements found in the fuels used for commercial steam generation, it is, as stated, a simple matter from the data of Table 8, to construct a formula for the amount of air theoretically required for the complete combustion of a pound of any fuel. This may be expressed as follows:

Pounds air required per pound fuel=

$$11.52\ C + 34.56\ (H - \frac{O}{8}) + 4.32\ S \qquad (23)$$

where C, H, O and S represent the percentages by weight of carbon, hydrogen, oxygen and sulphur.* As in the case of formula (*4*), the term $(H - \frac{O}{8})$ assumes that all of the oxygen constituent is free to unite with the hydrogen to form water vapor, such an assumption in the computation of the amount of air required leading to a negligible error. This formula, reduced to the simpler form in which it is ordinarily used becomes

Pounds air required per pound fuel=

$$34.56\ (\frac{C}{3} + [H - \frac{O}{8}] + \frac{S}{8}) \qquad (24)$$

In the case of gaseous fuels, it would be necessary, in order to make use of formula (*24*), to break the hydro-carbons into their constituent elements, and it is simpler to make use of a formula based directly upon the data of Table 8. For this class of fuels the formula may be expressed as follows:

Pounds air required per pound fuel=

$$2.46\ CO + 34.56\ H_2 + 17.28\ CH_4 + 13.29\ C_2H_2 + 14.81\ C_2H_4 + 16.13\ C_2H_6 + 6.10\ H_2S - 4.32\ O_2 \qquad (25)$$

With gaseous fuels, where the analysis is commonly given on a volumetric basis, it is sometimes desirable to express the amount

*While the constants are those determined in the calculations for Table 8.

of air required in terms of cubic feet. On the basis of the data of Table 9, formula (*25*), becomes then

Cubic feet air required per cubic foot gas=

$$2.39(CO+H_2)+9.56\ CH_4+11.98\ C_2H_2+14.35\ C_2H_4+16.74\ C_2H_6-4.78\ O_2 \qquad (26)$$

Products of Combustion

The data of Table 8, also makes it possible to determine directly what the products of theoretically perfect combustion will be.

Products of combustion per pound fuel:

$$CO_2=3.667\ C$$

$$H_2O=9\ (H-\frac{O}{8})+H_2O$$

$$S\ O_2=2.\ S$$

$$N_2=8.85\ C+26.56\ H_2+3.32\ S+N_2$$

With the actual weights of the products of combustion thus known, they may be expressed in terms of percentage by weight, and if desired these latter values may readily be transformed into values giving percentages by volume.

As in the case of air required for combustion it is perhaps simpler to express the products of combustion of a gaseous fuel directly in terms of the data of Table 8.

Products of combustion, one pound fuel=

$$CO_2=1.57\ CO+2.75\ CH_4+3.39\ C_2H_2+3.14\ C_2H_4+2.93\ C_2H_6+CO_2$$

$$H_2O=9\ (H-\frac{O}{8})+2.25\ CH_4+0.69\ C_2H_2+1.29\ C_2H_4+1.80\ C_2H_6+0.53\ H_2S+H_2O$$

$$SO_2=1.88\ H_2S$$

$$N_2=1.89\ CO+26.56\ H_2+13.28\ CH_4+10.21\ C_2H_2+12.38\ C_2H_4+12.40\ C_2H_6+4.69\ H_2S+N_2$$

Expressed in volumetric terms:

Products of combustion, one cubic foot fuel =

$$CO_2 = CO + CH_4 + 2\ C_2H_2 + 2\ C_2H_4 + 2\ C_2H_6 + CO_2$$

$$H_2O = H + 2\ CH_4 + C_2H_2 + 2\ C_2H_4 + 3\ C_2H_6 + H_2O + H_2S$$

$$SO_2 = H_2S$$

$$N_2 = 1.89\ CO + 1.89\ H_2 + 7.56\ CH_4 + 9.45\ C_2H_2 + 11.35\ C_2H_4 + 13.24\ C_2H_6 + 5.67\ H_2S + N_2$$

Combustion Data From Gas Analysis

A flue gas analysis may be used, as will be shown, in conjunction with the analysis which would result from the perfect combustion of a fuel, to give the necessary data for a computation of combustion losses. Its generally accepted use, however, is its application in a formula which is assumed to give directly the weight of dry gas per pound of carbon or of fuel burned, which weight is that used in combustion loss calculations. This formula is

Pounds dry gas per pound carbon =

$$\frac{11\ CO_2 + 8\ O_2 + 7\ (CO + N_2)}{3\ (CO_2 + CO)} \qquad (27)$$

where the symbols represent the proportionate parts by volume of the constituents of the gas analyzed.

Properly used, this formula gives results which are accurate well within the limits of error of boiler testing. Unfortunately, however, the formula is too frequently presented without explanation of its derivation, or without discussion of the assumption upon which it is based, and for intelligent use, it would appear that both of these factors should be considered.

The only gases which can exist in the products resulting from the combustion of carbon are carbon-dioxide, carbon monoxide, oxygen and nitrogen, all of the carbon coming from the fuel while the oxygen and nitrogen are from the air introduced for combustion.

If we assume that all of the dry gas resulting from the combustion of any fuel is due to the oxidization of carbon, either free or combined, which assumption would be correct if we neglect the sulphur constituent of the fuel, the weight of carbon burned

in the fuel times the weight of dry products of combustion per pound of carbon must equal the total weight of dry products. This, expressed as a formula, is, in terms of weights per pound of fuel,

Weight of C burned x dry gas per pound C=total dry gas

or

$$\text{Dry gas per pound C} = \frac{\text{Total dry gas per pound fuel}}{\text{Weight C burned per pound fuel}} \quad (a)$$

The actual weight of carbon in the fuel must reappear in the flue gases in the same amount either as carbon dioxide or carbon monoxide and (*a*) may be written as

$$\text{Dry gas per pound C} = \frac{\text{Total dry products}}{\text{Weight C in flue gases}} \quad (b)$$

This relation must hold whether expressed in terms of actual weights or in terms of percentage by weights and (*b*) thus may be written

$$\text{Dry gas per pound C} = \frac{100}{\frac{3}{11}\,CO_2 + \frac{3}{7}\,CO}$$

or

$$\text{Dry gas per pound C} = \frac{CO_2 + CO + O_2 + N_2}{\frac{3}{11}\,CO_2 + \frac{3}{7}\,CO} \quad (c)$$

where the symbols represent percentages by weight.

Formula (*c*) may be transferred to volumetric form by multiplying each term by its relative density (see page 19) and becomes

$$\text{Dry gas per pound C} = \frac{11\,CO_2 + 8\,O_2 + 7\,(CO + N_2)}{3\,(CO_2 + CO)} \quad (27)$$

the symbols representing the volumetric percentages of the constituent gases as given by a flue gas analysis.

The principal assumption of formula (*27*) is that the analysis as used is of dry gas.

All fuels in common use contain a greater or lesser amount of moisture. The loss due to such moisture is computed where a heat balance is given but the weight of this moisture is sometimes overlooked in computing total gas weight. All air supplied for combustion also contains a certain amount of moisture, and though this weight may be computed and the loss resulting therefrom determined, the weight is ordinarily inappreciable and the loss commonly included with the unaccounted losses.

Aside from the moisture in the fuel and in the air supplied for combustion, which moisture will appear as water vapor in the flue gases, there will also be an appreciable weight of water vapor due to the burning of the hydrogen content of the fuel. This weight, with perfect combustion, may be as high as 15 per cent of the total for certain gaseous fuels. (See by-product coke oven gas.)

We have then present in the flue gases but not measured in the ordinary analysis, a considerable amount of moisture in the form of water vapor. Water is commonly used as the displacement medium in the collection of the sample of gas for analysis, and further, during the analysis itself the gas sample comes into contact with water. The effect of these various factors tends toward a saturation of the gas being analyzed and from the results obtained with all classes of fuel the assumption seems warranted that such gases are actually saturated. Under these conditions proportionate parts of the water vapor content of the gas will be absorbed with the different constituents of such gas and the resulting analysis may be safely assumed to be that of a dry gas. How nearly correct such an assumption is may be seen from the various examples of the computations of combustion data which follow.

A further source of error in formula (*27*) is one resulting from the presence of sulphur in numerous fuels. Such sulphur, as shown in Table 2, ordinarily burns to SO_2, which will be absorbed in the flue gas analysis as carbon dioxide. With fuels low in sulphur the error arising from this source is small and can be safely neglected. With fuels high in sulphur and low in carbon, however, as in the case of certain middle western coals, the error may be of sufficient amount to warrant consideration. In an example given later for a coal containing 4.42 S and 61.25 per cent C. the error is shown to be as great as 4 per cent.

It is entirely possible in determining the weight of dry products of combustion per pound of fuel from formula (*27*) to modify the actual carbon weight as given by the ultimate analysis to correct for the sulphur content of the fuel, and where accuracy is desired, and the sulphur content is appreciable, such a correction should be made.

The first term of formula (*27*), viz. ($11\ CO_2 \div [3(CO_2+CO)]$) represents not only the weight of CO_2 resulting from the combustion of carbon, but includes as well the SO_2 resulting from the combination of sulphur. If the weight of CO_2 and SO_2 resulting from the combustion of one pound of carbon and one pound of sulphur, respectively, were the same, the necessary correction, for the proper determination of the weight of dry products of combustion per pound of fuel from formula (*27*) could be made simply adding the sulphur content to the carbon content of the fuel. The CO_2 resulting from the combustion of one pound of carbon, however, is, from Table 8, 3.667 pounds, while the weight of SO_2 from one pound of sulphur is 2.00 pounds. The corrective factor must be in the ratio of these weights, and the correct value instead of being (C+S) will be $(C+\frac{S}{1.833})$. The weight of dry products of combustion per pound of fuel then instead of being

$$\frac{11\ CO_2+8\ O_2+7\ (N_2+CO)}{3\ (CO_2+CO)}\ x\ C \qquad (27\text{-}a)$$

should be, where accuracy is desired,

$$\frac{11\ CO_2+8\ O_2+7\ (N_2+CO)}{3\ (CO_2+CO)}\ x\ (C+\frac{S}{1.833}) \qquad (27\text{-}b)$$

Formula (*27*) then, may be accepted as correct for any fuel, for the computation of the data which it is presumed to give, namely, the weight of dry gas per pound of carbon, or by multiplying the weight so determined by the weight of carbon in the fuel properly corrected for the sulphur equivalent, the weight of dry gas per pound of fuel. It is not to be accepted however, without additional data in the way of fuel analysis, in the computation of total gas weights or in the computation of the amount of air supplied for combustion. The chief reason for this statement lies in the fact that practically all fuels contain a certain amount of hydrogen. The oxygen supplied for the combustion of this hydrogen does not appear in the dry flue gases and is not accounted for by formula (*27*), while the nitrogen which accompanied the oxygen so utilized does appear in the dry gases and in the analysis. It is not always made clear why, in spite of this fact, formula (*27*) can be safely used for the computation of the dry gas per pound of carbon or per pound of

fuel, and a word of explanation on this feature seems advisable. The carbon content of the fuel must all appear in the dry gases in the exact amount * as in the fuel, either as carbon dioxide or as carbon monoxide. The basis of formula (*27*) is, as has been shown, simply the weight relation between a known quantity of one constituent of the dry gases (carbon) and the total weight of such gases, regardless of the composition of such total weight or the sources of its constituents, and with the weight and the percentage weight of a single constituent known, the total weight is obvious.

Air Supplied for Combustion

A number of formulae based upon a volumetric flue gas analysis have been offered for the computation of the weight of air supplied per pound of fuel burned. While certain of these formulae give reasonably accurate results for specific classes of fuels, none is applicable to all fuels.

Unquestionably the best method of determining the weight of air supplied, and in fact the only method that may be safely used for all fuels, is through the use of formula (*27*) or (*27-b*) giving the dry products of combustion per pound of carbon or of fuel, and in conjunction with this formula, certain data of perfect combustion which may be obtained from Table 8.

It is customary and proper to report a fuel analysis on a dry or moisture free basis. On such a basis, where total gas weights are desired, the water vapor in the flue gases resulting from the presence of moisture in the fuel should be computed separately, and in the proposed method of determining the air supplied for combustion, neglecting the moisture content of such air, the results obtained are in terms of dry fuel.

Assuming complete combustion of the hydrogen present in any fuel, the water vapor content of the flue gases from this source must be a constant weight regardless of the amount of air supplied for combustion. This weight may be readily determined from the percentage of hydrogen in the fuel (total weight per pound) and the data of Table 8. Obviously then, the total weight of the products of combustion per pound of dry fuel for any amount of excess air must equal the dry products of combustion per pound as given by formula (*27-b*) plus the constant weight of

* Less unconsumed C in ash.

the water vapor formed in the burning of the hydrogen content. Further, the total weight of the products of combustion of the dry fuel must equal the weight of air supplied plus the weight of the fuel which is burned, and appears in the flue gases. Hence,

Dry products per pound fuel + H_2O from H_2 =
Dry air supplied per pound + (Weight fuel in gases)*

or

Dry air supplied per pound = Dry products per pound + H_2O from H_2 — (Weight fuel in gases)

From the weight of air supplied as so determined, and the weight theoretically required as computed from Table 8 or by formula (*25*), the amount of excess air may be readily found, as may be the ratio of air supplied to that theoretically necessary, which value, assuming complete combustion, is in the last analysis, the true measure of the efficiency of combustion.

This method, as stated, necessitates an analysis of the fuel as well as of the flue gases. There is one of the formulae offered for the direct computation of the amount of air supplied for combustion, based on a volumetric flue gas analysis alone, which while it is not applicable to all fuels, will give reasonably accurate results for most solid and liquid fuels, and for this reason should be discussed. This formula as ordinarily given is

$$\text{Dry air supplied per pound } C = \frac{3.032\ N_2}{CO_2 + CO} \quad (28)$$

where the symbols represent the volumetric percentages of carbon monoxide, carbon dioxide and nitrogen.

This formula with the constant 3.032 is derived as follows: The last term of formula (*27*)

$$\frac{7\ N_2}{3\ (CO_2 + CO)}$$

must represent the weight of nitrogen supplied by the air, plus the weight of nitrogen in the fuel itself. For the particular fuel (coal containing one per cent N_2) and combustion conditions (20 per cent excess air) from which the constant 3.032 in formula (*28*) was determined, the nitrogen content of the fuel was approximately $\frac{1}{800}$ of the total weight of nitrogen in the dry products of combustion.

*Ex. in the case of coal (1-Ash).

Since the nitrogen is 76.85 per cent by weight of the air supplied for combustion, the weight of air supplied per pound of carbon for the conditions assumed would be then

$$\frac{7\ (N_2 - \frac{N_2}{800})}{.7685 \times 3\ (CO_2 + CO)} = \frac{3.032\ N_2}{(CO_2 + CO)}$$

Since the correction to the term $7\ N_2$ will vary not only with the nitrogen content of the fuel but also with the amount of excess air supplied, and for this reason the formula must be only approximate at best, it would perhaps be best to make no attempt to correct for the nitrogen content of the fuel, in which case the constant instead of being 3.032 would become 3.036, and the weight of air supplied per pound of carbon will be

$$\frac{7\ N_2}{.7685 \times 3\ (CO_2 + CO)} = \frac{3.036\ N_2}{(CO_2 + CO)} \qquad (28a)$$

For the determination of the weight of dry air per pound of fuel from this formula, where the sulphur content of the fuel is low, this value may be obtained by multiplying formula (*28a*) by the pecentage by weight of carbon in the fuel. With fuels high in sulphur a correction may be made to modify the carbon content as in the case of the determination of the dry products per pound of fuel, though in view of the approximate nature of the formula, this refinement is probably not warranted. If such modification is desired, the corrective factor instead of being based, as in the previous case, upon the ratio of SO_2 to CO_2, should be based on the weight ratio of N_2 in the products of combustion of one pound of carbon and one pound of sulphur respectively, or from Table 8, 3.32 to 8.85. With such correction the weight of dry air supplied per pound of fuel would be

$$\frac{3.036\ N_2}{(CO_2 + CO)} \times (C + \frac{S}{2.667}) \qquad (28b)$$

The error of this formula will depend as stated, not only upon the nitrogen content of the fuel but also upon the amount of excess air supplied. While this error is practically negligible for solid and liquid fuels, in gaseous fuels it is sufficiently large to make the formula useless. The reason for this is clear if we consider blast furnace gas, where with ordinarily good combustion, the weight of nitrogen in the fuel itself may be almost as

great as that in the air introduced for combustion. (See example following.)

Numerous other formulae are offered for the determination of the ratio of air to that required. Such formulae, however, are based on the relations of nitrogen and oxygen existing in the flue gases, and are incorrect in that they do not take into consideration the fact that while, with most fuels, practically all of the nitrogen shown was introduced with the air supplied, this nitrogen is composed of that which accompanied the oxygen used in the combustion of carbon and appearing as carbon dioxide or carbon monoxide, and that which accompanied the oxygen used in the combustion of hydrogen, this latter amount of oxygen not appearing in the flue gas analysis. Hence the relation of nitrogen and oxygen in the dry flue gases cannot be used as indicative of similar relations existing in the air supplied. This criticism does not apply to formula (*28*) since this is an expression of carbon-nitrogen relations, and does not involve oxygen. The criticism of formula (*28*) as to nitrogen content of the fuel is applicable to the air ratio formulae usually offered. These air ratio formulae are ordinarily so subject to error and are so narrowly applicable that they are not included here.

The errors resulting from the proper use of flue gas analysis in the computation of combustion data are well within the error of boiler testing as a whole. There is, however, a real source of possible error in the making of the analyses, and in practise there are several features that should be carefully watched where accuracy in the fuel results is desired. These are of sufficient importance to warrant discussion and, assuming a proper design of analysis apparatus, the errors to be guarded against may be listed as follows:

First. Care should be taken that the sample of gas for analysis is an average sample. This is the feature which should be most carefully watched and is perhaps the most difficult of achievement. No hard and fast rules can be laid down for the methods of obtaining such average sample and it is largely a question of commonsense. The sample should be drawn from the main body of the gases and in a location where the possibility of dilution through air infiltration is a minimum.

Second. Absorption reagents should be reasonably fresh. Each reagent is capable of absorbing a definite amount of one of the constituent gases, this amount ordinarily being expressed in terms of volume of the absorbing medium, and a check should be kept on the total absorption. Where solutions are weak and absorption is not accomplished within a relatively short time, there is a tendency to accept the absorption as complete, which results in an inaccurate analysis.

Third. There is a tendency, particularly in the case of inexperienced operators, toward attempting to force the absorption. With reasonable fresh solutions, the gas should be brought into contact with the absorption tubes at least twice, and oftener as the solutions become weaker. In the case of oxygen, where, through attempting to force the rapidity of the analysis, absorption is not complete, erroneous results both as to oxygen and carbon monoxide content will be obtained since the absorbing reagent for the latter will also absorb oxygen.

Fourth. Analyses should be completed. Too frequently it is assumed that the carbon dioxide content alone, or the carbon dioxide and oxygen content is sufficient, but often the efficiency seemingly indicated by a high carbon dioxide content alone, would be more than offset by the fact that appreciable amounts of carbon monoxide were present and not analyzed.

In connection with the completing of an analysis, it is perhaps well to warn the operator not to start an analysis with the fixed idea that the sum of the carbon dioxide, oxygen and carbon monoxide must total to a fixed amount. This sum will vary with different classes of fuel and to an extent with different fuels of the same class. In hand-firing it will vary in samples taken at different times relative to the firing intervals, as the volatile elements are consumed to a greater extent directly after than before firing. How great the variation in the sum of these three constituents may be is indicated by the analyses resulting from the combustion of different fuels, as shown in the examples of computations of combustion data given hereafter.

COMBUSTION LOSSES

WITH the methods of computing combustion data available, it is now possible to consider the losses which occur in the burning of fuel under a steam boiler. Certain of such losses are not, strictly speaking, combustion losses, but it is customary to consider all losses together. The results of the computations of these losses constitute the "heat balance" of a boiler test which indicates the distribution of losses. Where a test is not accompanied by such a heat balance, or at least by sufficient data from which it may be computed, the results should not ordinarily be accepted as absolutely reliable.

These losses, together with the methods of their computations are:

First. Loss due to the moisture contained in the fuel.

All of the moisture in the fuel must be heated from atmospheric temperature (or from the temperature of the fuel where this is above that at atmosphere) to 212 degrees, the temperature at which steam is formed, assuming atmospheric pressure, and the steam so formed must be heated to the temperature of the furnace gases. Since in passing over the boiler heating surface the temperature will ultimately be reduced to that of the escaping gases, the first and last temperatures are those that need be considered.

The B. t. u. loss from this source per pound of fuel may be expressed

$$\text{Per cent Moisture} \times [(212-t)+970.4+.48\,(T-212)] \quad (29)$$

where t = temperature of atmosphere or fuel,

T = temperature of escaping flue gases,

970.4 = latent heat of evaporation at atmospheric pressure,

.48 = mean specific heat of superheated steam at atmospheric pressure. (In reality this value will vary slightly with different values of T, but the variation is small and .48 may be taken as representing the value for ordinary exit gas temperatures.)

In the case of gaseous fuels introduced into the furnace the moisture content already exists as vapor. The temperature of this vapor is the same as that of the gas with which it is mixed,

but its partial pressure is below that corresponding to such temperature, except where the gas is saturated, a condition which rarely occurs. Such water vapor then, existing at a temperature above saturation, or above the temperature corresponding to its partial pressure, is in reality superheated steam, and in increasing its temperature to that of the escaping gases the question of the expenditure of heat in changing its condition, *i. e.*, latent heat expenditure, is not involved.

The loss due to the moisture content of gaseous fuels will be expressed then

$$\text{Per cent moisture } .48\ (T-t) \qquad (30)$$

Where the gaseous fuel is introduced into the furnace at or near atmospheric temperatures the specific heat of the water vapor content will be considerably lower than 0.48. The use of this value, however, as the mean specific heat over the range t—T will lead to a negligible error only.

Second. Loss due to moisture formed in the burning of hydrogen.

From Table 8, each pound of hydrogen burned will result in the formation of 9 pounds of water vapor. This moisture must be heated as in the case of the moisture in the fuel and the loss may be expressed

$$\text{Per cent } H_2 \times 9\ [(212-t)+970.4+.48\ (T-212)] \qquad (31)$$

In the case of hydrogen, since water is an actual product of combustion the latent heat must be taken into consideration, regardless of the fact that the moisture appears in the products of combustion as water vapor, and whether the fuel is solid, liquid or gaseous.

Third. Loss due to moisture in the air.

The weight of water vapor per pound of dry air may be determined from readings of the wet and dry bulb thermometers and a set of psychrometric tables.

This weight times the weight of dry air supplied per pound of fuel, as determined by the methods which have been indicated, will give the total moisture in the air supplied per pound of fuel (W). Since this moisture is already in the form of water vapor, as in the case of the moisture content of gaseous fuels, the question

of the expenditure of heat in changing its condition is not involved and the loss from this source will be

$$W \times .48 \times (T - t) \qquad (32)$$

Fourth. Loss due to heat carried away in the dry chimney gases.

The weight of gas per pound of fuel burned (W) may be computed by the methods indicated. In the case of solid fuels when the weight of dry gas per pound of carbon as given by formula (27) is multiplied by the carbon content of the fuel, the proper value of the carbon for use is the percentage of carbon actually burned and appearing in the flue gases, *i. e.*, the carbon content corrected for any unconsumed carbon in the ash and refuse.

The heat lost in the dry chimney gases then, is measured by this weight of gas (W) and the difference between the temperature of the escaping gases and that of the atmosphere. It may be expressed

$$W (T - t) \ .24 \qquad (33)$$

where .24 is taken as the mean specific heat of the gas between these temperature limits. Since this specific heat will vary with the temperature of the escaping gases and with their composition, it would be well to compute its value where the most accurate results are desired. The value .24 though probably somewhat low, is, however, ordinarily accepted.

Fifth. Loss due to the incomplete combustion of carbon.

This loss may be expressed

$$\frac{CO}{CO_2 + CO} \times C \times 10160 \qquad (34)$$

in which C is the weight of carbon which is burned and appears in the flue gases, *i. e.*, corrected for solid fuels, as in the case of the proceeding loss, for such unconsumed carbon as appears in the ash. The constant 10160 represents the number of heat units generated in burning one pound of carbon *in carbon monoxide* to carbon dioxide. The term $\frac{CO}{CO_2 + CO}$, in which the symbols

(N. B.—The loss due to moisture in the air is frequently not computed and is included with the unaccounted losses.)

represent the *volumetric* percentages of the constituents as shown by analysis, is an expression denoting the *weight* of the carbon present in the carbon monoxide constituents, and perhaps needs explanation.

From formula (*27*), the weight of carbon monoxide in the flue gas is given by

$$\frac{7\ CO}{3\ (CO_2 + CO)}$$

If this expresses the *weight* of carbon monoxide in terms of volumetric percentages of the constituents, obviously the weight of carbon in the carbon monoxide must be $\frac{3}{7}$ of this amount or $\frac{CO}{CO_2 + CO}$.

Sixth. Loss due to carbon appearing in unconsumed refuse.

This loss may ordinarily be determined only in the case of solid fuels. It is expressed

$$\frac{c \times C}{100} \times 14600 \qquad (35)$$

where c=weight of ash per pound of fuel,

C=per cent of unconsumed combustible matter in the ash,

$c \times C$=weight of unconsumed carbon in terms of total carbon per pound of fuel.

The unconsumed combustible matter in the refuse is assumed to be entirely carbon for which 14600 B. t. u. per pound is taken as the approximate heat value. This assumption will give rise to an error which is negligible.

Seventh. Radiation and unaccounted losses.

These losses which are either impossible or impracticable to measure, include:

(*a*) Radiation loss, which in terms of percentage will vary with the size of the unit, the condition of the setting and like factors.

(*b*) Losses due to unburned volatile hydrocarbons, and

(*c*) Loss due to the combination of carbon and moisture, with the consequent formation of hydrogen ($C + H_2O = CO + 2oH$), which may or may not be burned. This action may occur when moist fuel is thrown on an incandescent fuel bed.

(*d*) Other losses not accounted above.

The total of the losses under item seven is taken as the difference between 100 per cent and the boiler efficiency plus the sum of the six losses as computed.

The actual computations of two typical heat balances are given in examples hereafter.

Of the losses listed which can be computed the first, second and third items are only to an extent controllable. Since the moisture content of all fuels and of air, and the hydrogen content of most fuels must be accepted as found, the only manner is which these losses may be kept at a minimum for a given fuel is by the reduction of the exit gas temperature to the lowest possible or practicable figure. Assuming proper combustion, the exit gas temperature is a function of the heat absorbing ability of the boiler, and is thus rather a question of boiler design than of combustion proper. If, on the other hand, the efficient absorbing power of the boiler is assumed, these three losses are controllable to the extent that exit gas temperatures are dependent upon combustion.

The fourth loss is more truly a combustion loss though since it is affected by exit gas temperatures this too is dependent on boiler design. Obviously with a given fuel, and for a given exit gas temperature, the greater the gas weight, *i. e.*, the greater the excess air, the greater the loss of heat in the chimney gases. This loss is kept at a minimum when complete combustion is made to approach perfect combustion.

The fifth loss is entirely a combustion loss and is to be prevented only by the admission of sufficient air for complete combustion and in a manner that such complete combustion is assured. In endeavoring to bring about such conditions the tendency is toward the introduction of too great an amount of air, in which case the carbon monoxide loss will be reduced or prevented at the expense of a loss resulting from the fourth source. It is to be remembered that while the absence of carbon monoxide in the flue gases indicates complete combustion, it does not of necessity indicate efficient combustion.

The sixth loss, which can only be determined with solid fuels, is not properly speaking a combustion loss and is the result of the physical factors entering into the design of furnaces, stokers or grates, and in the operation of the apparatus. Assuming

the best of design this loss is minimized through proper operation.

It will be noted from the foregoing that the two main factors upon which the extent of all combustion losses depend are the amount of air supplied for combustion and the temperature of the gases leaving the boiler heating surfaces. The factor of air supply can, within limits, be controlled, but if we assume the ability of a boiler to absorb heat efficiently, the factor of exit gas temperature can only be controlled to the extent that it is dependent upon air supply. In view of this fact the effect of air supply on exit gas temperature must be considered.

On first thought it would appear that since large quantities of excess air introduced into the furnace would reduce the temperature of the products of combustion before the boiler heating surfaces are encountered, such dilution would result in lower exit gas temperatures and it is of course entirely possible to carry this dilution to the products of combustion in the furnace to a point where such a decrease in ultimate temperature would result. In practise, however, even where the amounts of excess air correspond to the most inefficient combustion, this excess instead of decreasing, tends to increase the exit gas temperature.

The common explanation of this apparent phenomenon is that the excess air in passing through and mingling with the actual products of combustion absorbs heat from such products more readily than will the boiler heating surfaces, and a considerable portion of the heat so absorbed is carried off in the escaping gases. Such a statement offers by far the simplest explanation, and one which accounts for a part at least of the increase of exit gas temperature with an increase of excess air. The other factor leading to such a result is dependent upon heat transfer rates, difference in temperature between the gases and the absorbing surface, the percentage of total heat absorbed through radiation and the percentage of total absorption through convection. Any attempt to explain the high exit temperatures accompanying large amounts of excess air on such a basis leads to a complication of theories that are not within the scope of the present article.

If we accept the foregoing as correct, it is obvious that the stack loss due to excess air will increase with such excess, not

only because additional amounts of air must be heated from atmospheric temperature to that of the escaping gases, but also because the ultimate temperature will, within ordinary limits, be higher as the amount of excess is increased, the two factors thus combining to increase the possible loss under item four, as listed previously.

The effect of incomplete combustion in the furnace may be either to reduce or increase exit gas temperatures.

If the combustion of a given fuel is not completed in the furnace before the combustible gases come into contact with the boiler heating surfaces, the temperature evolved in the furnace, and hence the temperature of the products of combustion, will be less than if such combustion were complete. If such unconsumed or partially consumed gases pass from the boiler and up the stack without encountering somewhere in the setting sufficient additional oxygen for the completion of combustion, or temperatures under which combination resulting in further combustion will take place, the result on the ultimate flue gas temperature would be to reduce it below what it would be if combustion had been complete in the furnace. If, on the other hand, these partially consumed gases encounter at some point in their passage over the boiler heating surface sufficient oxygen for continued combustion with a temperature above the ignition point, such combustion will occur. In boiler practise this is known as delayed or secondary combustion, and ordinarily will take place at such a point within the boiler setting as to appreciably increase the temperature of the exit gases above that which would result from complete combustion in the furnace.

SMOKE

THOUGH there is perhaps no phase of combustion that has been so fully discussed as that which results in the production of smoke, the common understanding of the loss from this source is at best vague, and based in part at least on misconception. For this reason a brief consideration of smoke is included here, regardless of the amount of data on the subject available elsewhere.

Of the numerous and frequently unsatisfactory definitions of smoke that have been offered, that of the Chicago Association of Commerce Committee in its report on "Smoke Abatement and the Electrification of Railway Terminals in Chicago," is perhaps the best. This report defines smoke as "the gaseous and solid products of combustion, visible and invisible, including . . . . mineral and other substances carried into the atmosphere with the products of combustion."

From the standpoint of combustion loss it is necessary to lay stress on the term "visible and invisible." The common conception of the extent of loss is based on the visible smoke, and such conception is so general that practically all if not all smoke ordinances are based on visibility, density or color of escaping stack gases. As a matter of fact, the color of smoke, which is imparted to the gases by particles of carbon, cannot be taken as an indication of the stack loss. The invisible or practically colorless gases issuing from a stack may represent a combustion loss many times as great as that due to the actual carbon present in the gases, and but a small amount of such carbon is sufficient to give color to large volumes of invisible gases which may or may not represent direct combustion losses. A certain amount of color may also be given to the gases by particles of flocculent ash and mineral matter, neither of which represents a combustion loss. The amount of such material in the escaping gases may be considerable where stokers of the forced draft type are used and heavy overloads are carried.

The carbon or soot particles in smoke from solid fuels is not due to the incomplete combustion of the fixed carbon content of the fuel. They result rather from the non-combustion or incomplete combustion of the volatile and heavy hydrocarbon

constituents, and it is the wholly or partially incomplete combustion of these constituents that causes smoke from all fuels solid, liquid or gaseous.

If the volatile hydrocarbons are not consumed in the furnace, and there is no secondary combustion, there will of course be a direct loss resulting from the non-combustion of these constituents. While certain of these unconsumed gases may appear as visible smoke, the loss from this source cannot be measured with the ordinary flue gas analysis apparatus, and must of necessity be included with the unaccounted losses.

Where the combustion of the hydrocarbon constituents is incomplete a portion of the carbon component ordinarily appears as soot particles in the smoke. In the burning of hydrocarbons the hydrogen constituent unites with oxygen before the carbon; for example, in the case of ethylene (C_2H_4)

$$C_2H_4 + 2\ O = 2\ H_2O + 2\ C$$

If after the hydrogen is "satisfied" there is sufficient oxygen present with which that carbon component may unite, and temperature conditions are right, such combination will take place and combustion will be complete. If on the other hand sufficient oxygen is not present, or if the temperature is reduced below the combining temperature of carbon and oxygen, regardless of the amount of oxygen present, the carbon will pass off unconsumed as soot.

The direct loss from unconsumed carbon passing off in this manner is probably rarely in excess of one per cent of the total fuel burned even in the case of the densest smoke. The loss due to unconsumed or partially consumed volatile hydrocarbons, on the other hand, though not indicated by the appearance of the gases issuing from a stack, may represent a very appreciable percentage of the total fuel fired.

While the loss represented by the *visible* constituents of smoke leaving a chimney may ordinarily be considered negligible, there is a loss due to the presence of unconsumed carbon and tarry hydrocarbons in the products of combustion which, while not a direct combustion loss, may result in a much greater loss in efficiency than that due to visible smoke. These constituents adhere to the boiler heating surfaces, and acting as an insulating

layer greatly reduce the heat absorbing ability of such surfaces. From the foregoing it is evident that the stack losses indicated by smoke, whether visible or invisible, result almost entirely from improper combustion. Assuming a furnace of proper design and fuel burning apparatus of the best, there will be no objectionable smoke where there is good combustion. On the other hand a smokeless chimney is not necessarily indicative of proper or even of good combustion. Large quantities of excess air in diluting the products of combustion naturally tend toward a smokeless stack, but the possible combustion losses corresponding to such an excess air supply have been shown.

GENERAL CONCLUSIONS

IN view of the great number of factors involved in the combustion of any fuel, and the great variation in the characteristics not only of different classes of fuel, but of different fuels of the same class, it is obvious that the specific requirements for the proper combustion of an individual fuel must be considered as a distinct problem. It is possible, however, from the foregoing, to draw certain general conclusions as to the combustion requirements of *any* fuel, whether solid, liquid or gaseous, and since such conclusions form the basis of the design of all combustion apparatus, they are worthy of careful note.

These general requirements of proper combustion may be summarized as follows:

First. The admission of an air supply such as will assure sufficient oxygen for complete combustion.

Second. Since complete combustion is not of necessity efficient combustion, it must be secured without permitting the dilution of the products of combustion with excess air. It follows then, that

Third. The air supply should be admitted at the proper time and in such a manner that the oxygen of the air comes into free and intimate contact with the combustible substances of the fuel. In the case of solid fuels this means not only into contact with the solid particles of the oxidizable substances, but also with the combustible gases as they are distilled from the fuel.

Fourth. The gases must be maintained at a temperature at or above their ignition point until combustion is complete. Theoretically, as has been indicated, the most efficient combustion is that resulting in the maximum temperature possible. In practice, there are frequently factors which, from the standpoint of operating commercial efficiency, makes it advisable to keep furnace temperatures somewhat below those which could be obtained were this the sole factor involved.

Fifth. An additional requirement which has to do with the physical rather than the chemical aspect of combustion is that proper provision must be made for the expansion of gases during the period of their combustion.

In considering combustion it is necessary, though perhaps difficult for the average boiler user, to distinguish between the purely chemical changes that accompany oxidization and the purely physical aspect of the later transformation of heat energy in the passage of the products of combustion through the boiler, *i. e.*, the absorption of heat by the boiler from such gases. The efficiency of combustion is thus independent of the ability of the boiler under which combustion takes place to absorb heat, and in the requirements of proper combustion just summarized such ability is either assumed or neglected.

From the general conclusions drawn it would seem perhaps a simple matter to meet the requirements of proper combustion. Unfortunately, however, such is not the case and it is, as stated heretofore, the physical and mechanical details encountered in attempting to fulfill such requirements that render the problem of proper combustion difficult. Assuming proper furnace *form* and adequate combustion temperatures, the problem is solely one of air admission and admixture. The factors entering into the problem and the methods used to bring about the desired results are so widely varied for different fuels, that it is necessary, as stated, to consider each class of fuel specifically for any but the most general statements.

THE COMPUTATION OF COMBUSTION DATA

THE methods of computing combustion data as discussed in the foregoing, and the very widely differing data resulting from the combustion of different classes of fuel, *i. e.*, the wide variation in possible or probable flue gas analyses, products of combustion and air supplied per pound of fuel for different combustion conditions are, to the writer's mind, best illustrated by example.

For this reason typical examples of the different classes of fuel used for the commercial production of heat under steam boilers are considered in the following. Except in the case of coal where the analyses vary over a wide range, the analyses of the fuels taken are sufficiently near an average to allow the results to be plotted in such manner that for a given flue gas analysis (*i. e.*, per cent CO_2), the weight of the products of combustion and the amount of excess air corresponding to such analysis, may be determined directly for the specific class of fuel considered with a degree of accuracy sufficient for approximate work. Such graphic representations are therefore included.

COAL

Given a coal having the following ultimate analysis:

	Per Cent
Carbon	79.86
Hydrogen	5.02
Oxygen	4.27
Nitrogen	1.86
Sulphur	1.18
Ash	7.81
	100.00
Moisture	2.90 per cent
B. t. u., per pound	14351

With perfect combustion the oxygen and air required, and the products of combustion per pound of coal will be as follows:

	Weight per Pound Coal Pounds	Required—Pounds		Products of Combustion—Pounds per Pound Coal				
		O_2	Air	CO_2	O_2	N_2	H_2O	SO_2
C	.7986	2.130	9.200	2.929	. . .	7.070	. . .	. . .
H_2	.0502	.402	1.735	. . .	. . .	1.333	.452	. . .
O_2	.0427	. . .	. . .	. . .	.043	. . .	. . .	. . .
N_2	.0186	. . .	. . .	. . .	. . .	.019	. . .	. . .
S	.0118	.012	.051	. . .	. . .	.039	. . .	.024
Ash	.0781	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	1.0000	2.544	10.986	2.929	.043	8.461	.452	.024
O_2 in Coal		.043	.186*	. . .	.043	.143*	. . .	. . .
		2.501	10.800	2.929	.000	8.318	.452	.024
SO_2 as CO_2		. . .	. . .	.024	. . .	. . .	. . .	.024
		2.501	10.800	2.953	.000	8.318	.452	.000

*Air and N_2 equivalents of O_2 in coal.

The weight of air theoretically required for the combustion of one pound of coal is then 10.800 pounds. For each 20 per cent in excess of this amount (*i. e.*, each 2.160 pounds above 10.800) there will appear in the products of combustion

$$2.160 \times .2315 = .500 \text{ pounds } O_2$$
$$2.160 \times .7685 = 1.660 \text{ pounds } N_2$$

and the weights of the products of combustion per pound of coal for varying amounts of excess air will be:

TABLE A

	Weight Products Perfect Combustion	Weight Products—Varying Amounts of Excess Air—Pounds				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	2.953	2.953	2.953	2.953	2.953	2.953
O_2	.000	.500	1.000	1.500	2.000	2.500
N_2	8.318	9.978	11.638	13.298	14.958	16.618
H_2O	.452	.452	.452	.452	.452	.452
	11.723	13.883	16.043	18.203	20.363	22.523

Expressed in terms of percentage weight, these values are:

TABLE B

	Per Cent Weight Products Perfect Combustion	Per Cent Weight Products—Varying Amounts of Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	25.190	21.270	18.407	16.223	14.502	13.111
O_2	.000	3.602	6.233	8.240	9.821	11.100
N_2	70.955	71.872	72.543	73.054	73.458	73.782
H_2O	3.855	3.256	2.817	2.483	2.219	2.007
	100.000	100.000	100.000	100.000	100.000	100.000

Expressed in terms of percentage weight of dry products of combustion these values are:

TABLE C

	Per Cent Weight Dry Products Perfect Combustion	Per Cent Weight Dry Products—Varying Amounts of Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	26.200	21.987	18.940	16.636	14.831	13.380
O_2	.000	3.723	6.414	8.450	10.044	11.327
N_2	73.800	74.290	74.646	74.914	75.125	75.293

If we convert these percentages by weight of the dry products of combustion into terms of percentage by volume after the method given on page 19, the values as given in Table C become:

TABLE D

	Per Cent Volume Dry Products Perfect Combustion	Per Cent Volume Dry Products—Varying Amounts of Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	18.428	15.285	13.057	11.396	10.110	9.085
O_2	.000	3.559	6.080	7.960	9.415	10.575
N_2	81.572	81.156	80.863	80.644	80.475	80.340
	100.000	100.000	100.000	100.000	100.000	100.000

For the purpose of comparing the results as computed as above with those obtained through the use of the combustion

formulae which have been discussed, assume that the coal is burned with 40 per cent excess air and the flue gas analysis by volume shows 13.057 per cent CO_2, 6.080 per cent O_2 and 80.683 per cent N_2.

The weight of dry products of combustion per pound of carbon will be, from formula (*27*):

$$\frac{11 \times 13.057 + 8 \times 6.080 + 7 \times 80.863}{3 \times 13.057} = 19.359 \text{ pounds}$$

Multiplying this value by the weight of carbon per pound of dry coal, we have as the weight of dry products per pound of dry coal

$$19.359 \times .7986 = 15.460 \text{ pounds}$$

as against a value, in Table A, of

$$16.043 - .452 = 15.591 \text{ pounds}$$

an error of 0.131 pounds, or 0.84 per cent. If the carbon weight is corrected for the sulphur equivalent as explained on page 54, the value of C becomes

$$.7986 + (.012^* \div 1.833) = .8051$$

and the weight of dry products of combustion per pound of dry coal becomes

$$.8051 \times 19.359 = 15.586 \text{ pounds}$$

which checks with the value of Table A within 0.03 per cent.

The total weight of gas per pound of coal fired will be the sum of the dry products per pound of dry coal, the water vapor from the hydrogen, and the weight of moisture per pound of coal,

or $$15.591 + .452 + .029 = 16.072 \text{ pounds}$$

The weight of dry air supplied per pound of carbon, from formula (*28*), will be

$$\frac{3.036 \times 80.863}{13.057} = 18.802 \text{ pounds}$$

*Weight of S used in computing SO_2.

The weight of dry air supplied per pound of coal, using the actual carbon weight, will be

$$18.802 \times .7986 = 15.015 \text{ pounds}$$

while the weight using the carbon weight corrected for the sulphur equivalent (in this case the ratio of the nitrogen in the air supplied for the combustion of carbon and sulphur to CO_2 and SO_2 respectively) will be

$$18.802 \times [.7986 + (.012 \div 2.667)] = 15.100 \text{ pounds}$$

The actual weight of air supplied per pound of dry fuel will be the total products of combustion per pound of dry coal, less the weight per pound which is burned and appears in such products, or, from Table A and the weight of ash as given by the analysis

$$16.043 - (1 - .078) = 15.121 \text{ pounds}$$

For this particular coal then, the errors above, using the uncorrected and the corrected values of carbon as applied to formula (*28*), are 0.70 per cent and 0.14 per cent respectively.

Formulae (*28*, *28a* and *28b*) will, as stated, give results within reasonably accurate limits, with fuels having a low nitrogen content, the error varying with the percentage of nitrogen and with the amount of air used for combustion. With fuels of high nitrogen content, the error may be as great as 80—90 per cent (see Blast Furnace Gas) and for such fuels these formulae are not to be relied upon.

The heat of combustion per pound of dry coal computed from formula (*4*) will be

$$14600 \times .7986 + 62000 \left(.0502 - \frac{.0427}{8}\right) + 4050 \times .0118$$
$$= 14492 \text{ B. t. u.}$$

as against the calorimetrically determined value 14351 B. t. u., an error of 0.99 per cent.

To indicate the amount of possible error with high sulphur fuels, in the determination of the dry products of combustion per pound of fuel from formula (*27*) where the carbon content is not corrected for the sulphur equivalent, let us assume a coal having the analysis given below. The weight of oxygen and air

theoretically required, and the weight of the products of perfect combustion per pound of dry coal will be as follows:

	Weight per Pound Coal Pounds	Required—Pounds		Products of Combustion—Pounds per Pound Coal				
		O_2	Air	CO_2	O_2	N_2	H_2O	SO_2
C	.6125	1.6335	7.0560	2.2460	. . .	5.4225	. . .	. . .
H_2	.0448	.3584	1.5483	. . .	. . .	1.1898	.4032	. . .
O_2	.1062	. . .	. . .	. . .	.1062	. . .	. . .	. . .
N_2	.0100	. . .	. . .	. . .	. . .	.0100	. . .	. . .
S	.0442	.0442	.1909	. . .	. . .	.1467	. . .	.0884
Ash	.1823	. . .	. . .	. . .	. . .	. . .	. . .	. . .
		2.0361	8.7952	2.2460	.1062	6.7690	.4032	.0884
O_2 in Coal .		.1062	.4588	. . .	.1062	.3526	. . .	. . .
		1.9299	8.3364	2.2460	.0000	6.4164	.4032	.0884
SO_2 as CO_2		. . .	. . .	.0884	. . .	. . .	. . .	.0884
		1.9299	8.3364	2.3344	.0000	6.4164	.4032	.0000

The air required per pound of dry coal for perfect combustion is thus 8.3364 pounds. If we assume the coal to be burned with 20 per cent excess air, there will appear in the products of combustion, in addition to the weights just given,

$$1.6673 \times .2315 = .3860 \text{ pounds } O_2$$
$$1.6673 \times .7685 = 1.2813 \text{ pounds } N_2$$

With 20 per cent excess air then, the weight of the products of combustion per pound of dry coal, these weights expressed in terms of percentage weight, expressed in terms of percentage weight of dry products, and expressed in terms of percentage volume of dry products, are as follows:

	Weight Products Pounds	Per Cent Weight Products	Per Cent Weight Dry Products	Per Cent Volume Dry Products
CO_2	2.3344	21.572	22.407	15.603
O_2	.3860	3.567	3.705	3.547
N_2	7.6977	71.135	73.888	80.850
H_2O	.4032	3.726	. . .	. . .
	10.8213	100.000	100.000	100.000

Under the assumed conditions, the weight of dry gas per pound of carbon will be from formula (*27*):

$$\frac{11 \times 15.603 + 8 \times 3.547 + 7 \times 80.850}{3 \times 15.603} = 16.3635 \text{ pounds}$$

Multiplying this value by .6125, the weight of carbon per pound of dry coal, we have as the dry products per pound

$$16.3635 \times .6125 = 10.022 \text{ pounds}$$

as against the computed value above

$$10.8213 - .4032 = 10.418 \text{ pounds}$$

an error of approximately 4.0 per cent. If, on the other hand, the weight of carbon is corrected for the sulphur equivalent, we have

$$16.3635 \times [.6125 + (.0442 \div 1.833)] = 10.417 \text{ pounds}$$

which value checks with the computed weight.

WOOD

Given a wood (pine) having the following ultimate analysis:

	Per Cent
Carbon	50.31
Hydrogen	6.20
Oxygen	43.08
Nitrogen	.04
Ash	.37
	100.00
Moisture	46.10 per cent
Heat value per pound dry wood, B. t. u.	9153

With perfect combustion the oxygen and air required per pound of dry wood and the products of combustion per pound will be as follows:

	Weight Per Pound Wood Pounds	Required—Pounds		Products of Combustions-Pounds Per Pound Wood			
		O_2	Air	CO_2	O_2	N_2	H_2O
C	.5031	1.342	5.796	1.845	. . .	4.454	. . .
H_2	.0620	.4960	2.143	. . .	. . .	1.647	.558
O_2	.4308	. . .	. . .	. . .	.4308	. . .	. . .
N_2	.0004	. . .	. . .	. . .	. . .	.000	. . .
Ash	.0037	. . .	. . .	. . .	. . .	. . .	. . .
		1.838	7.939	1.845	.4308	6.101	.558
		.431	1.862*	. . .	.4308	1.431*	. . .
		1.407	6.077	1.845	.000	4.670	.558

*Air and N_2 equivalents of O_2 in wood.

The weight of air theoretically required for the combustion of one pound of dry wood is thus 6.077 pounds. For each 20 per cent in excess of this weight (*i. e.*, each 1.2154 pounds of air above 6.077), there will appear in the products of combustion.

$$1.2154 \times .2315 = .2814 \text{ pounds } O_2$$
$$1.2154 \times .7685 = .9340 \text{ pounds } N_2$$

and the weight of the products of combustion per pound of dry wood for varying amounts of excess air will be:

TABLE A

	Weight Products Perfect Combustion	Weight Products—Varying Amounts Excess Air—Pounds				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	1.845	1.845	1.845	1.845	1.845	1.845
O_2	.000	.281	.563	.844	1.126	1.407
N_2	4.668	5.602	6.536	7.470	8.404	9.338
H_2O	.558	.558	.558	.558	.558	.558
	7.071	8.286	9.502	10.717	11.933	13.148

Expressed in terms of percentage weight, these values are:

TABLE B

	Per Cent Weight Products Perfect Combustion	Per Cent Weight Products—Varying Amounts Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	26.093	22.267	19.417	17.216	15.461	14.033
O_2	.000	3.391	5.925	7.875	9.436	10.701
N_2	66.016	67.608	68.786	69.702	70.427	71.022
H_2O	7.891	6.734	5.872	5.207	4.676	4.244
	100.000	100.000	100.000	100.000	100.000	100.000

Expressed in terms of percentage weight of dry products of combustion these values are:

TABLE C

	Per Cent Weight Dry Products Perfect Combustion	Per Cent Weight Dry Products—Varying Amounts Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	28.328	23.875	20.628	18.162	16.219	14.655
O_2	.000	3.636	6.295	8.307	9.899	11.175
N_2	71.672	72.489	73.077	73.531	73.882	74.170
	100.000	100.000	100.000	100.000	100.000	100.000

Converting the percentages by weight into terms of percentage by volume of dry products of combustion, the values of Table C become:

TABLE D

	Per Cent Volume Dry Products Perfect Combustion	Per Cent Volume Dry Products—Varying Amounts Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	20.097	16.721	14.313	12.514	11.115	9 999
O_2	.000	3.501	6.006	7.870	9.327	10.483
N_2	79.903	79.778	79.681	79.616	79.558	79.518
	100 000	100.000	100.000	100.000	100.000	100.000

In order to compare these results with those obtained through the use of the combustion formulae, assume that the wood is burned with 60 per cent excess air and that the flue gas analysis shows 12.514 per cent CO_2, 7.870 per cent O_2, and 79.616 per cent N_2.

The dry gas per pound of carbon from formula (*27*) will be

$$\frac{11 \times 12.514 + 8 \times 7.870 + 7 \times 79.616}{3 \times 12.514} = 20.189 \text{ pounds}$$

Since the wood contains no sulphur, no correction for this constituent is necessary to the carbon weight, and the weight of dry products of combustion per pound of dry wood is

$$20.189 \times .5031 = 10.157 \text{ pounds}$$

which checks with the value of Table A, viz.:

$$10.717 - .558 = 10.159 \text{ pounds}$$

Since for each pound of dry wood burned there are .4610 pounds of contained moisture, and since from the hydrogen content there will appear in the flue gases .558 pounds of water vapor, the total weight of products per pound of wood will be

$$10.159 + 9\ (.062) + .461 = 11.178 \text{ pounds}$$

The weight of dry air supplied per pound of carbon from formula (*28*) is

$$\frac{3.036 \times 79.616}{12.514} = 19.316 \text{ pounds}$$

and the dry air supplied per pound of wood

$$19.316 \times .5031 = 9.718 \text{ pounds}$$

Since the nitrogen content of the wood is so small as not to appear in the computations of the products of combustion, this value will check with the weight of air determined from Table A and the ash weight, viz.:

$$10.717 - (1. - .004) = 9.721 \text{ pounds}$$

or with the value from the theoretical amount of air required and 60 per cent excess, viz.:

$$6.077 + (.6 \times 6.077) = 9.722 \text{ pounds}$$

If we accept the analysis taken as typical of all woods, the approximate weights of the products of combustion per pound

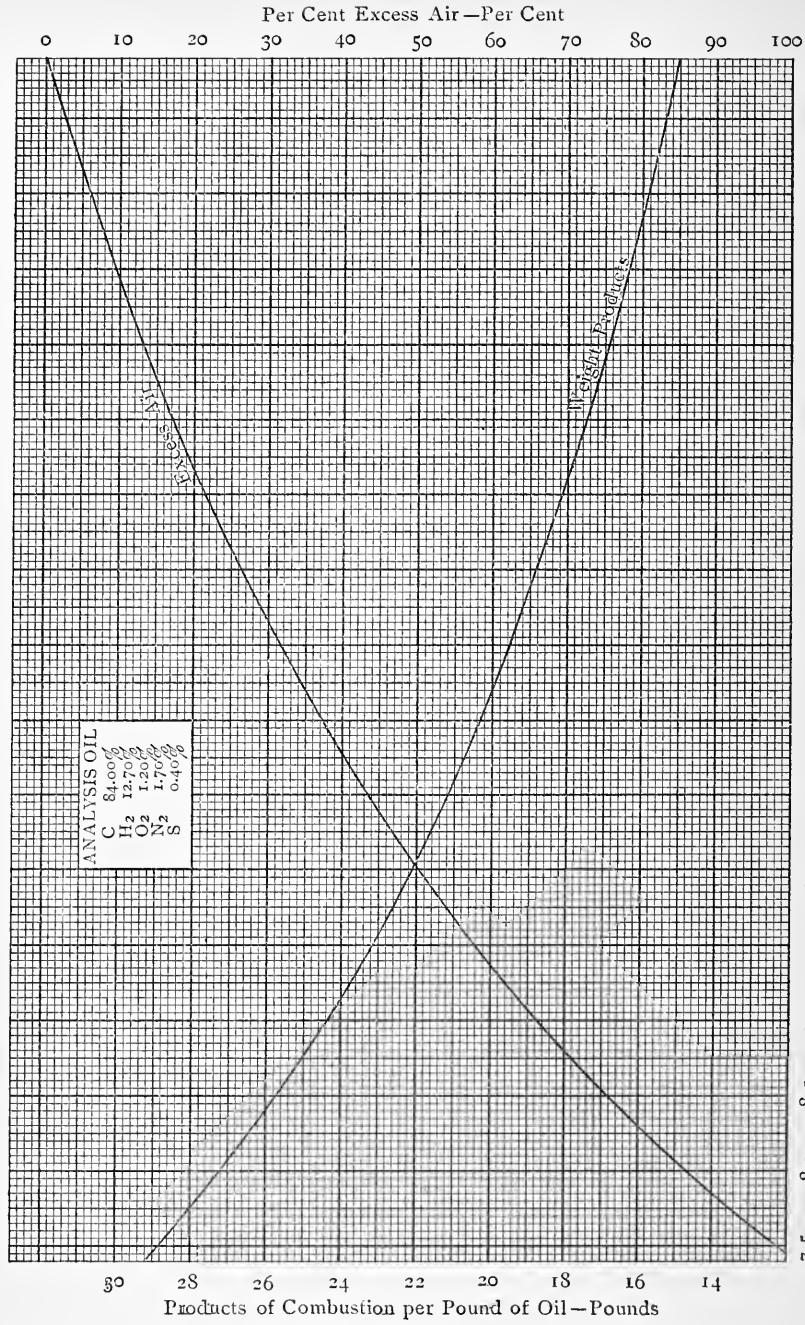

FIGURE 2

OIL. CO_2—Products per Pound Oil. CO_2—Per Cent of Excess Air

of dry wood corresponding to different percentages of carbon dioxide, and the amount of excess air which such weights represent, may be determined graphically from Figure 2.

OIL

Given an oil having an ultimate analysis as follows:

	Per Cent
Carbon	84.00
Hydrogen	12.70
Oxygen	1.20
Sulphur	0.40
Nitrogen	1.70
	100.00

With perfect combustion the oxygen and air required per pound of oil, and the products of combustion per pound will be as follows:

	Weight per Pound Oil Pounds	Required—Pounds		Products of Combustion—Pounds per Pound of Oil				
		O_2	Air	CO_2	O_2	N_2	H_2O	SO_2
C	.8400	2.240	9.677	3.080	. . .	7.437	. . .	. . .
H_2	.1270	1.016	4.389	. . .	. . .	3.373	1.143	. . .
O_2	.0120	. . .	. . .	. . .	.0120	. . .	. . .	. . .
S	.0040	.004	.017	. . .	. . .	.013	. . .	.008
N_2	.0170	. . .	. . .	. . .	. . .	.017	. . .	. . .
		3.260	14.083	3.080	.012	10.840	1.143	.008
O_2 in Oil		.012	.052*	. . .	.012	.040*	. . .	. . .
		3.248	14.031	3.080	.000	10.800	1.143	.008
SO_2 as CO_2		. . .	. . .	.008	. . .	. . .	. . .	.008
		3.248	14.031	3.088	.000	10.800	1.143	.000

*Air and N_2 equivalents of O_2 in oil.

The weight of air theoretically required for the combustion of one pound of oil is then 14.031 pounds. For each 20 per cent supplied in excess of this weight of air (*i. e.*, each 2.8062

pounds above 14.031), there will appear in the products of combustion

$$2.8062 \times .2315 = .6496 \text{ pounds of } O_2$$
$$2.8062 \times .7685 = 2.1566 \text{ pounds of } N_2$$

and for varying amounts of excess air the weights of the products of combustion per pound of oil will be:

TABLE A

	Weight Products Perfect Combustion	Weight Products—Varying Amounts Excess Air—Pounds				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	3.088	3.088	3.088	3.088	3.088	3.088
O_2	.000	.650	1.299	1.949	2.598	3.248
N_2	10.800	12.957	15.113	17.270	19.426	21.583
H_2O	1.143	1.143	1.143	1.143	1.143	1.143
	15.031	17.838	20.643	23.450	26.255	29.062

Expressed in terms of percentage weight, these values are:

TABLE B

	Per Cent Weight Products Perfect Combustion	Per Cent Weight Products—Varying Amounts Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	20.544	17.311	14.959	13.169	11.762	10.626
O_2	.000	3.644	6.293	8.311	9.895	11.176
N_2	71.852	72.637	73.211	73.646	73.990	74.265
H_2O	7.604	6.408	5.537	4.874	4.353	3.933
	100.000	100.000	100.000	100.000	100.000	100.000

Expressed in terms of percentage weight of dry products of combustion, these values are:

	Per Cent Weight Dry Products Perfect Combustion	Per Cent Weight Dry Products—Varying Amounts Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	22.235	18.496	15.836	13.844	12.297	11.061
O_2	.000	3.894	6.662	8.737	10.345	11.634
N_2	77.765	77.610	77.502	77.419	77.358	77.305
	100.000	100.000	100.000	100.000	100.000	100.000

Converting these percentages by weight of the dry products of combustion into terms of percentage by volume, the values of Table C become:

TABLE D

	Per Cent Volume Dry Products Perfect Combustion	Per Cent Volume Dry Products—Varying Amounts Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	15.395	12.686	10.788	9.384	8.304	7.446
O_2	.000	3.672	6.240	8.144	9.605	10.769
N_2	84.605	83.642	82.972	82.472	82.091	81.785
	100.000	100.000	100.000	100.000	100.000	100.000

Assume, for the purpose of comparing the data thus computed with the results obtained from the use of the combustion formulae, that the oil is burned with 20 per cent excess air and that the flue gas analysis shows 12.686 per cent CO_2, 3.672 per cent O_2, and 82.972 per cent N_2.

The weight of dry products of combustion per pound of carbon is, from formula (*27*)

$$\frac{11 \times 12.686 + 8 \times 3.672 + 7 \times 83.642}{3 \times 12.686} = 19.823 \text{ pounds}$$

Multiplying this value by the weight of carbon per pound of oil we have as the weight of dry gas per pound of oil.

$$19.823 \times .84 = 16.651 \text{ pounds}$$

as against the value from Table A

$$17.838 - 1.143 = 16.695 \text{ pounds}$$

If the carbon weight is corrected for the sulphur equivalent, the two values may be made to check exactly, and we have as the weight of dry gas per pound of oil

$$19.823 \times [.84 + (.004 \div 1.833)] = 16.695 \text{ pounds}$$

The total gas weight per pound of oil will be the dry gas weight plus the weight of moisture resulting from the burning of .127 pounds of hydrogen, or

$$16.695 + (.127 \times 9) = 17.838 \text{ pounds}$$

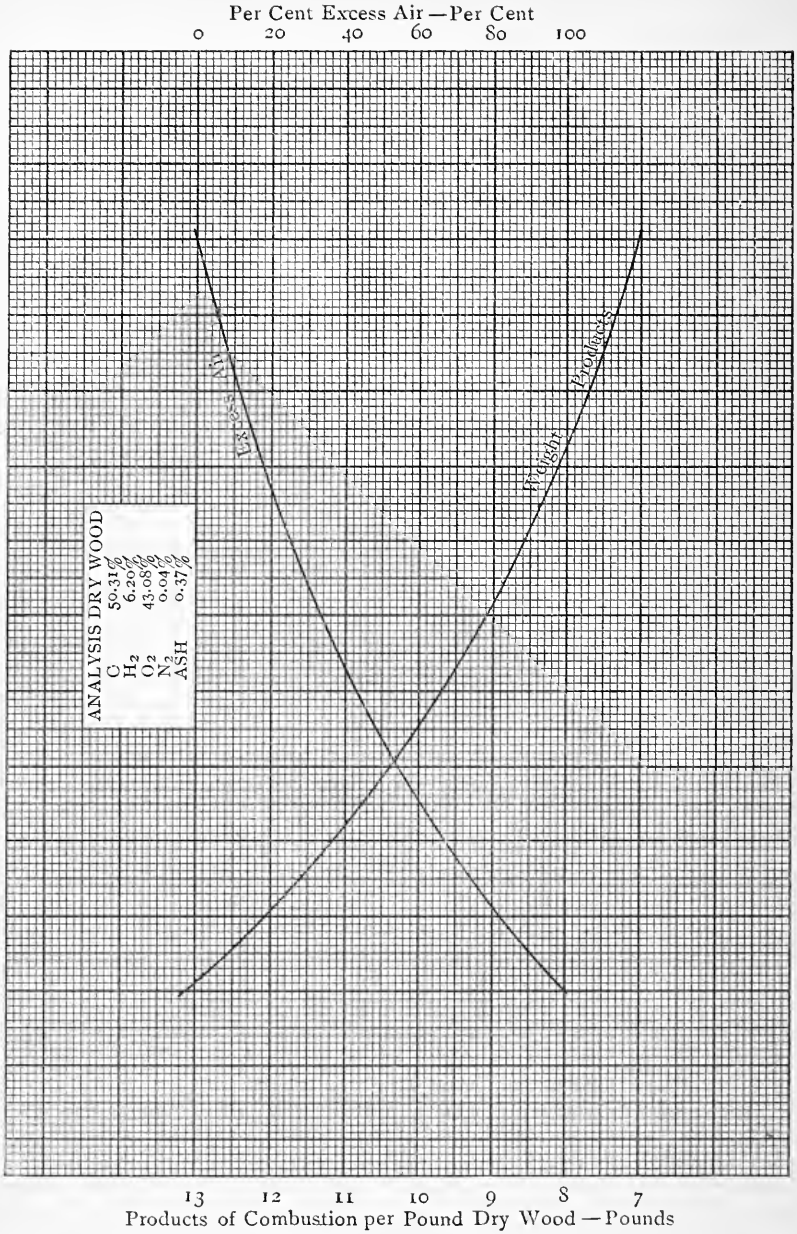

FIGURE 3

WOOD. CO_2—Products per Pound Dry Wood. CO_2—Per Cent of Excess Air

and since all of the fuel will appear in the products of combustion, the weight of air supplied per pound of oil will be

$$17.838 - 1 = 16.838 \text{ pounds}$$

This value checks with the computed value of the theoretical requirement plus 20 per cent excess, or

$$14.041 + (.20 \times 14.041) = 16.837 \text{ pounds}$$

The weight of air supplied per pound of carbon from formula (*28*) is

$$(3.036 \times 83.64) \div 12.686 = 20.017 \text{ pounds}$$

and the weight per pound of oil, using the corrected carbon weight,

$$20.017 \times [.84 + (.004 \div 2.667)] = 16.843 \text{ pounds}$$

the slight difference between this value and the actual weight being due to the nitrogen content of the oil.

If the analysis of oil taken be accepted as typical for this class of fuel, the weight of the products of combustion per pound of oil for different percentages of CO_2, and the per cent of excess air corresponding to such CO_2 may be determined directly from Figure 3.

NATURAL GAS

Given a natural gas (Ohio) having an analysis by volume as follows:

	Per Cent
Carbon Monoxide	0.45
Hydrogen	1.82
Methane	93.33
Ethylene	0.25
Hydrogen Sulphide	0.18
Oxygen	0.35
Carbon Dioxide	0.22
Nitrogen	3.40
	100.00

Converting this analysis by volume to one by weight we have:

	Volume per Cubic Foot		Weight per Cubic Foot		Weight Pounds				Per Cent by Weight
CO	.0045	x	.07806	=	.000351	÷	.046058	=	0.762
H_2	.0182	x	.00562	=	.000102	÷	.046058	=	0.221
CH_4	.9333	x	.04500	=	.041999	÷	.046058	=	91.188
C_2H_4	.0025	x	.07808	=	.000195	÷	.046058	=	0.423
H_2S	.0018	x	.09600	=	.000173	÷	.046058	=	0.376
O_2	.0035	x	.08921	=	.000312	÷	.046058	=	0.677
CO_2	.0022	x	.12341	=	.000272	÷	.046058	=	0.591
N_2	.0340	x	.07807	=	.002654	÷	.046058	=	5.762
	1.0000				.046058				100.000

The weight of the gas is thus, under standard conditions, .046058 pounds per cubic foot.

With perfect combustion the oxygen and air required per pound of gas, and the products of combustion per pound will be as follows:

	Weight Per Pound Gas Pounds	Required Pounds		Products of Combustion—Pounds Per Pound Gas				
		O_2	Air	CO_2	O_2	N_2	H_2O	SO_2
CO	.00762	.0044	.0188	.0120	. . .	.0144	. . .	. . .
H_2	.00221	.0177	.0764	. . .	. . .	.0587	.0199	. . .
CH_4	.91188	3.6475	15.7573	2.5077	. . .	12.1098	2.0517	. . .
C_2H_4	.00423	.0145	.0626	.0133	. . .	.0481	.0055	. . .
H_2S	.00376	.0053	.0229	. . .	. . .	.0176	.0020	.0071
O_2	.00677	. . .	. . .	. . .	.0068	. . .	. . .	. . .
N_2	.05762	. . .	. . .	. . .	. . .	.0576	. . .	. . .
CO_2	.00591	. . .	. . .	.0059	. . .	. . .	. . .	. . .
		3.6894	15.9380	2.5389	.0068	12.3062	2.0791	.0071
O_2 in Gas		.0068	.0294*	. . .	.0068	.0226*	. . .	. . .
		3.6826	15.9086	2.5389	.0000	12.2836	2.0791	.0071
SO_2 as CO_2		. . .	. . .	.0071	. . .	. . .	. . .	.0071
		3.6826	15.9086	2.5460	.0000	12.2836	2.0791	.0000

*Air and N_2 equivalents of O_2 present in gas.

The weight of air theoretically required for the combustion of one pound of gas is thus 15.9068 pounds. For each 20 per

cent in excess of this weight (*i. e.*, each 3.1817 pounds), there will appear in the products of combustion

$$3.1817 \times .2315 = .73656 \text{ pounds } O_2$$
$$3.1817 \times .7685 = 2.44513 \text{ pounds } N_2$$

and for varying amounts of excess air the weights of the products of combustion per pound of gas will be:

	Weight Products Perfect Combustion	Weight Products Varying Amounts Excess Air—Pounds				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	2.5460	2.5460	2.5460	2.5460	2.5460	2.5460
O_2	.0000	.7366	1.4731	2.2097	2.9462	3.6828
N_2	12.2836	14.7287	17.1739	19.6190	22.0641	24.5093
H_2O	2.0791	2.0791	2.0791	2.0791	2.0791	2.0791
	16.9087	20.0904	23.2721	26.4538	29.6354	32.8172

Expressed in terms of percentage weight these values are:

TABLE B

	Per Cent Weight Products Perfect Combustion	Per Cent Weight Products—Varying Amounts Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	15.057	12.673	10.940	9.624	8.591	7.758
O_2	.000	3.666	6.330	8.353	9.942	11.222
N_2	72.647	73.312	73.796	74.163	74.452	74.684
H_2O	12.296	10.349	8.934	7.860	7.015	6.336
	100.000	100.000	100.000	100.000	100.000	100.000

Expressed in terms of percentage weight of dry products of combustion these values are:

TABLE C

	Per Cent Weight Dry Products Perfect Combustion	Per Cent Weight Dry Products—Varying Amounts Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	17.168	14.136	12.013	10.445	9.239	8.283
O_2	.000	4.089	6.951	9.066	10.692	11.981
N_2	82.832	81.775	81.036	80.489	80.069	79.736
	100.000	100.000	100.000	100.000	100.000	100.000

Converting these percentages by weight of the dry products of combustion into terms of percentage by volume, the values of Table C becomes:

TABLE D

	Per Cent Volume Dry Products Perfect Combustion	Per Cent Volume Dry Products—Varying Amounts Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	11.652	9.535	8.067	6.991	6.169	5.520
O_2	.000	3.792	6.419	8.345	9.817	10.978
N_2	88.348	86.673	85.514	84.664	84.014	83.502
	100.000	100.000	100.000	100.000	100.000	100.000

For the purpose of comparison between the results so computed with those obtained from the combustion formulae, assume that the gas is burned with 40 per cent excess air and the flue gas analysis shows 8.067 per cent CO_2, 6.419 per cent O_2, and 85.514 per cent N_2.

The dry gas per pound of carbon from formula (27) will be:

$$\frac{11 \times 8.067 + 8 \times 6.419 + 7 \times 85.514}{3. \times 8.067} = 30.5226 \text{ pounds}$$

The weight of carbon per pound of gas will be:

From CO .00762 x $\frac{3}{7}$ = .003266
From CH_4 .91188 x $\frac{3}{4}$ = .683910
From C_2H_4 .00423 x $\frac{6}{7}$ = .003626
From CO_2 .00591 x $\frac{3}{11}$ = .001612

Total carbon .692414 pounds

Multiplying the weight of dry gas per pound of carbon by this value, we have as the dry gas per pound of gas burned

$$30.5226 \times .6924 = 21.134 \text{ pounds}$$

while the value from Table A for 40 per cent excess air is

$$23.2721 - 2.0791 = 21.193 \text{ pounds}$$

While the difference in these values is negligible, they may be made to check still more closely if the carbon weight is corrected for the sulphur equivalent. The weight of sulphur per pound of gas is

$$.00376 \times \tfrac{15}{16} = .00354 \text{ pounds}$$

The weight of dry gas per pound of gas burned, using the corrected carbon weight will be, then

$$30.5226 \times [.69241 + (.00354 \div 1.833)] = 21.192 \text{ pounds}$$

The weight of hydrogen per pound of gas will be

From H_2		=	.00221
From CH_4	.91188 x	$\frac{1}{4}$ =	.22797
From C_2H_4	.00423 x	$\frac{1}{7}$ =	.00060
From H_2S	.00376 x	$\frac{1}{16}$ =	.00023
	Total H_2		.23101 pounds

while the weight of water vapor in the products of combustion per pound of gas from this hydrogen, will be

$$.23101 \times 9 = 2.0791 \text{ pounds}$$

The total gas weight per pound of gas burned is thus

$$21.192 + 2.079 = 23.271 \text{ pounds}$$

With gaseous fuels, since the total weight of fuel burned will appear in the products of combustion, the air supplied per pound of fuel must equal the total products per pound less one, or, in the present instance, the air supplied per pound of gas will be

$$23.271 - 1 = 22.271 \text{ pounds}$$

which checks with the value of Table A, viz.:

$$15.9086 + (.40 \times 15.9086) = 22.272 \text{ pounds}$$

Since all gaseous fuels have a greater or lesser nitrogen content, this method for the computation of air supplied is much more accurate than the use of formula (*28*) and is also simpler.

The heat value per pound of this natural gas may be computed from the analysis by weight and Table 6 as follows:

I	Weight Per Pound		B. t. u. Per Pound I	=	B. t. u.
CO	.00762	x	4380	=	33
H_2	.00221	x	62000	=	137
CH_4	.91188	x	23850	=	21748
C_2H_4	.00423	x	21450	=	91
H_2S	.00376	x	7458	=	28
			B. t. u. per pound	=	22037

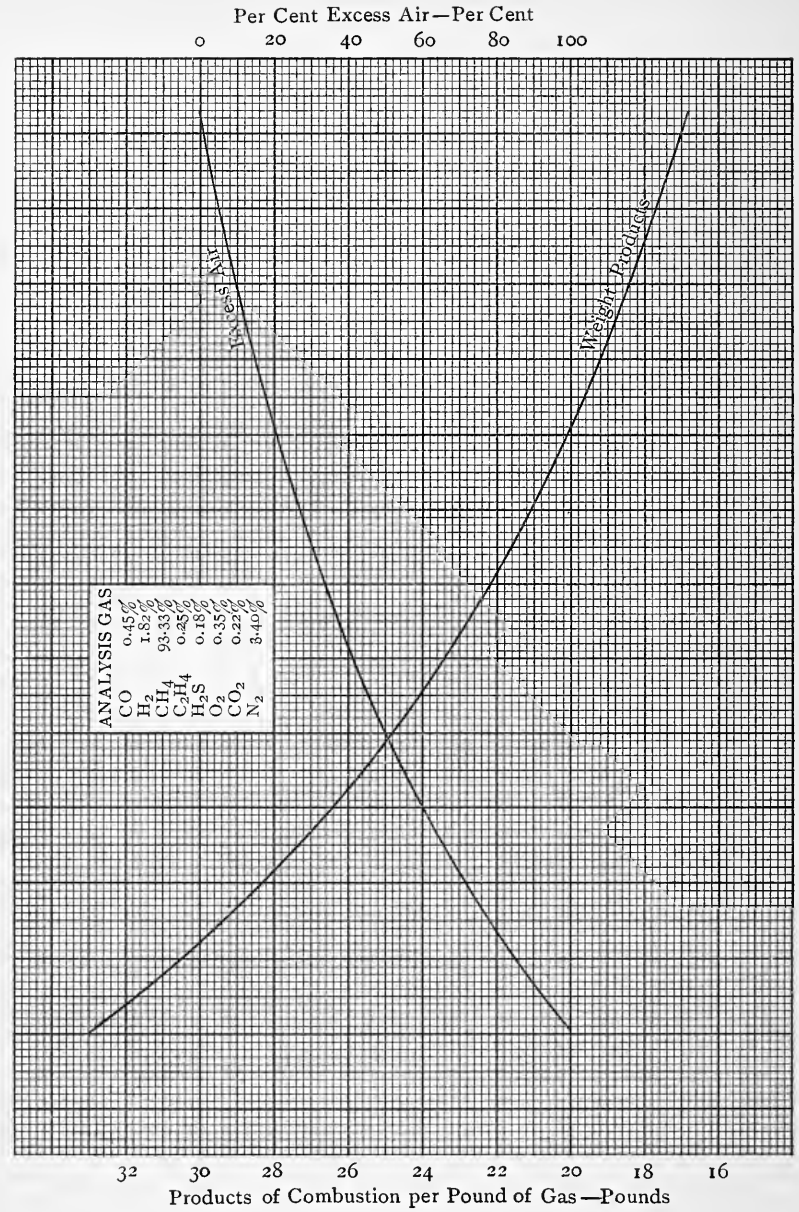

FIGURE 4

NATURAL GAS. CO_2—Products per Pound Gas

CO_2—Per Cent Excess Air

Since, as was shown, the gas under standard conditions weighs .046058 pounds per cubic foot, the heat value per cubic foot will be

$$22037 \times .046058 = 1015 \text{ B. t. u.}$$

To illustrate the methods of computation where volumetric results are desired, assume the same natural gas analysis as given above. The volumes of oxygen and air required for combustion and the volumetric products per cubic foot of gas will be as follows:

	Volume Per Cubic Foot Gas	Required Cubic Foot		Products of Combustion—Cubic Feet Per Cubic Foot Gas				
		O_2	Air	CO_2	O_2	N_2	H_2O	SO_2
CO	.0045	.00225	.01076	.0045	. . .	.0085	. . .	. . .
H_2	.0182	.00910	.04352	. . .	. . .	.0344	.0182	. . .
CH_4	.9333	1.86660	8.92608	.9333	. . .	7.0595	1.8666	. . .
C_2H_4	.0025	.00750	.03587	.0050	. . .	.0284	.0050	. . .
H_2S	.0018	.00270	.01291	. . .	. . .	.0102	.0018	.0018
O_2	.0035	. . .	. . .	. . .	.0035	. . .	. . .	. . .
CO_2	.0021	. . .	. . .	.0021	. . .	. . .	. . .	. . .
N_2	.0340	. . .	. . .	. . .	. . .	.0340	. . .	. . .
		1.88815	9.02914	.9449	.0035	7.1750	1.8916	.0018
O_2 in Gas		.00350	.01674*	. . .	.0035	.0132*	. . .	. . .
		1.88465	9.01240	.9449	.0000	7.1618	1.8916	.0018
SO_2 as CO_2		. . .	. . .	.0018	. . .	. . .	. . .	.0018
		1.88465	9.01240	.9467	.0000	7.1618	1.8916	.0000

*Air and N_2 equivalents of O_2 present in gas.

N. B.—It is of interest to note that because of the volumetric relations of CO, O_2 and CO_2, H_2, O_2 and H_2O, and H_2S, O_2, H_2O and SO_2, the total volume of products is *not* equal to the volume of the gas plus the volume of the air supplied.

One cubic foot of gas will thus require 9.0124 cubic feet of air for perfect combustion. If we assume, as in the computations on a weight basis, that the gas is burned with 40 per cent excess air, there will appear in the products of combustion in addition to the volumes given above

$$9.0124 \times .40 \times .2091 = .7538 \text{ cubic feet } O_2$$
$$9.0124 \times .40 \times .7909 = 2.8512 \text{ cubic feet } N_2$$

For 40 per cent excess air then, the volumes of the products of combustion, these volumes expressed in terms of percentage volume, and expressed in terms of percentage volume of dry products will be

	Volume Products per Cubic Foot	Per Cent Volume Products	Per Cent Volume Dry Products
CO_2	.9467	6.958	8.082
O_2	.7538	5.541	6.432
N_2	10.0130	73.597	85.514
H_2O	1.8916	13.904	. . .
	13.6051	100.000	100.000

The dry gas analysis as thus computed on a direct volumetric basis may be considered to check the analysis computed on the basis of weight, the maximum difference being 0.26 per cent. The slight difference is due to the fact that the weights of oxygen required per pound of the various combustible substances as given in Table 8 do not exactly check with the corresponding volumes of oxygen required as given in Table 9. The variation between these sets of corresponding values results from the use of the approximate instead of the accurate atomic and molecular weights in the computation of the proportionate parts by weight of the constituents of the combustible substances in Table 8. Any error arising from this source may be neglected.

The heat value per cubic foot of this natural gas may be computed from the analysis by volume and Table 6 as follows:

I	Volume per Cubic Foot		B. t. u. per Cubic Foot I		B. t. u.
CO	.0045	x	341.9	=	1.5
H_2	.0182	x	348.4	=	6.3
CH_4	.9333	x	1073.2	=	1001.6
C_2H_4	.0025	x	1674.8	=	4.2
H_2S	.0018	x	716.0	=	1.3
			B. t. u. per cubic foot		1014.9

This value checks with the value already computed from the analysis by weight.

If we accept the analysis taken as typical of natural gas, the approximate weights of the products of combustion per pound of gas burned, and the percentage of excess air, corresponding to different percentages of CO_2, for this class of fuel, may be determined directly from Figure 4.

BY-PRODUCT COKE OVEN GAS

Given a by-product coke oven gas having an analysis by volume as follows:

	Per Cent
Carbon Dioxide	0.75
Carbon Monoxide	6.00
Methane	28.15
Hydrogen	53.00
Nitrogen	12.10
	100.00

Converting the analysis by volume to one by weight, we have:

	Volume per Cubic Foot		Weight per Cubic Foot		Weight Pounds				Per Cent Weight
CO_2	.0075	x	.12341	=	.00093	÷	.03071	=	3.03
CO	.0600	x	.07806	=	.00468	÷	.03071	=	15.24
CH_4	.2815	x	.04500	=	.01267	÷	.03071	=	41.26
H_2	.5300	x	.00562	=	.00298	÷	.03071	=	9.70
N_2	.1210	x	.07807	=	.00945	÷	.03071	=	30.77
	1.0000				.03071				100.00

The weight of the gas is thus, under standard conditions, .03071 pounds per cubic foot.

With perfect combustion, the oxygen and air required per pound of gas, and the products of combustion per pound will be as follows:

	Weight per Pound Gas Pounds	Required per Pound Gas Pounds		Products of Combustion per Pound Gas		
		O_2	Air	CO_2	N_2	H_2O
CO_2	.0303	. . .	. . .	.030	. . .	. . .
CO	.1524	.087	.375	.239	.288	. . .
CH_4	.4126	1.651	7.132	1.135	5.481	.929
H_2	.0970	.776	3.352	. . .	2.576	.873
N_2	.3077	. . .	. . .	. . .	.308	. . .
	1.0000	2.514	10.859	1.404	8.653	1.802

The weight of air theoretically required for the combustion of one pound of gas is thus 10.859 pounds. For each 20 per

cent in excess of this amount (*i. e.*, each 2.172 pounds above 10.859) there will appear in the products of combustion

$$2.172 \times .2315 = .503 \text{ pounds } O_2$$

$$2.172 \times .7685 = 1.669 \text{ pounds } N_2$$

and for varying amounts of excess air the weights of the products of combustion per pound of gas will be:

TABLE A

	Weight Products Perfect Combustion	Weight Products—Varying Amounts of Excess Air—Pounds				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	1.404	1.404	1.404	1.404	1.404	1.404
O_2	.000	.503	1.006	1.509	2.012	2.515
N_2	8.653	10.322	11.991	13.660	15.329	16.998
H_2O	1.802	1.802	1.802	1.802	1.802	1.802
	11.859	14.031	16.203	18.375	20.547	22.719

Expressed in terms of percentage weight these values are:

TABLE B

	Per Cent Weight Products Perfect Combustion	Per Cent Weight Products—Varying Amounts of Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	11.839	10.007	8.665	7.641	6.833	6.180
O_2	.000	3.585	6.209	8.212	9.792	11.070
N_2	72.966	73.565	74.005	74.340	74.605	74.818
H_2O	15.195	12.843	11.121	9.807	8.770	7.932
	100.000	100.000	100.000	100.000	100.000	100.000

Expressed in terms of percentage weight of dry products of combustion these values are:

TABLE C

	Per Cent Weight Dry Products Perfect Combustion	Per Cent Weight Dry Products—Varying Amounts Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	13.960	11.482	9.749	8.472	7.490	6.712
O_2	.000	4.113	6.986	9.105	10.733	12.024
N_2	86.040	84.405	83.265	82.423	81.777	81.264
	100.000	100.000	100.000	100.000	100.000	100.000

Converting these percentages by weight of the dry products of combustion into terms of percentage by volume, the values of Table C become:

TABLE D

	Per Cent Volume Dry Products Perfect Combustion	Per Cent Volume Dry Products—Varying Amounts Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	9.359	7.666	6.491	5.629	4.968	4.447
O_2	.000	3.776	6.396	8.318	9.789	10.953
N_2	90.641	88.558	87.113	86.053	85.243	84.600
	100.000	100.000	100.000	100.000	100.000	100.000

For the purpose of comparing the results so computed with those obtained from the combustion formulae, assume that the gas is burned with 40 per cent excess air and that the flue gas analysis shows 6.491 per cent CO_2, 6.396 per cent O_2, and 87.113 per cent N_2.

The weight of dry gas per pound of carbon from formula (*27*) will be

$$\frac{11 \times 6.491 + 8 \times 6.396 + 7 \times 87.113}{3 \times 6.491} = 37.609 \text{ pounds}$$

The weight of carbon per pound of gas burned is

$$\begin{aligned} \text{From } CO_2 \quad & .0303 \times \tfrac{3}{11} = .0083 \\ \text{From } CO \quad & .1524 \times \tfrac{3}{7} = .0653 \\ \text{From } CH_4 \quad & .4126 \times \tfrac{3}{4} = .3094 \\ & \text{Total carbon} = .3830 \text{ pounds} \end{aligned}$$

and the weight of dry products per pound of gas

$$37.609 \times .3830 = 14.404 \text{ pounds}$$

The weight of hydrogen per pound of gas burned is

$$\begin{aligned} \text{From } H_2 \quad & = .0970 \\ \text{From } CH_4 \quad & .4126 \times \tfrac{1}{4} = .1032 \\ & \text{Total } H_2 \quad .2002 \text{ pounds} \end{aligned}$$

and the weight of water vapor formed in the burning of this hydrogen will be

$$.2002 \times 9 = 1.802 \text{ pounds}$$

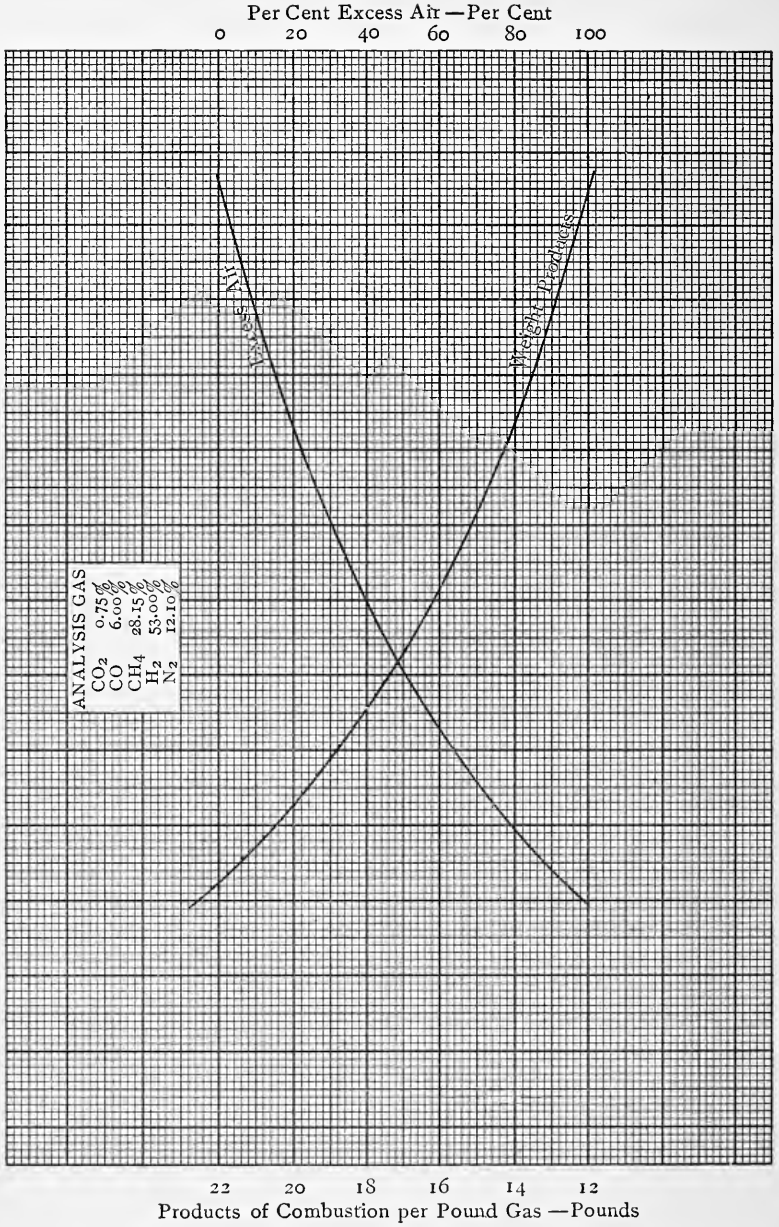

FIGURE 5

BY-PRODUCT COKE OVEN GAS. CO_2—Products per Pound Gas
CO_2—Per Cent Excess Air

The total weight of the products of combustion per pound of gas burned will thus be

$$14.404 + 1.802 = 16.206 \text{ pounds}$$

which value checks with the computed value of Table A for 40 per cent excess air.

Since all of the gas appears in the products of combustion, the weight of air supplied per pound of gas burned is

$$16.206 - 1 = 15.206 \text{ pounds}$$

which checks with the value computed from the weight of air theoretically required and 40 per cent excess air, viz.:

$$10.859 + (.40 \times 10.859) = 15.203 \text{ pounds}$$

The weight of air supplied per pound of carbon from formula (*28*) is

$$\frac{3.036 \times 87.113}{6.491} = 40.78 \text{ pounds}$$

and the weight of air per pound of gas

$$40.78 \times .3830 = 15.619 \text{ pounds}$$

The error resulting from the use of formula (*28*) for this particular gas is 2.7 per cent. In view of the nitrogen content of the gas (12.1 per cent by volume and 30.77 per cent by weight) this error appears smaller than might be expected, but this is due to the fact that while the nitrogen content is high, the total nitrogen per pound of gas is small as compared with the amount of nitrogen in the air required for combustion.

The heat value per pound of this gas may be computed from the analysis by weight and Table 6 as follows:

	Weight per Pound		B. t. u. per Pound		B. t. u.
CO	.1524	x	4380	=	667.5
CH_4	.4126	x	23850	=	9840.5
H_2	.0970	x	62000	=	6014.0
B. t. u. per pound				=	16522.0

and since, under standard conditions, the gas weighs .03071 pounds per cubic foot, the heat value per cubic foot will be

$$.03071 \times 16522 = 507.3 \text{ B. t. u.}$$

If we accept the analysis taken as typical of by-product coke oven gas, the weights of the products of combustion per pound of gas burned, and the percentage of excess air, corresponding to different percentages of carbon dioxide, may be determined directly from Figure 5

BLAST FURNACE GAS

Given a blast furnace gas having an analysis by volume, dry,* as follows:

	Per Cent
Carbon Dioxide	12.50
Carbon Monoxide	25.40
Hydrogen	3.50
Nitrogen	58.60

Converting the analysis by volume to one by weight, we have:

	Volume per Cubic Foot		Weight per Cubic Foot		Weight Pounds				Weight Per Cent
CO_2	.1250	x	.12341	=	.01543	÷	.08121	=	19.000
CO	.2540	x	.07806	=	.01983	÷	.08121	=	24.418
H_2	.0350	x	.00562	=	.00020	÷	.08121	=	.246
N_2	.5860	x	.07807	=	.04575	÷	.08121	=	56.336
	1.0000				.08121				100.000

The weight of the gas is thus, under standard conditions, .08121 pounds per cubic foot.

With perfect combustion the oxygen and air required per pound of gas, and the products of combustion per pound, will be as follows:

	Weight Per Pound Gas Pounds	Required per Pound Gas—Pounds		Products of Combustion per Pound Gas		
		O_2	Air	CO_2	N_2	H_2O
CO_2	.19000	. . .	. . .	.1900	. . .	. . .
CO	.24418	.1392	.6007	.3834	.4615	. . .
H_2	.00246	.0197	.0850	. . .	.0653	.0221
N_2	.56336	. . .	. . .	. . .	.5634	. . .
	. . .	.1589	.6857	.5734	12.000	.0221

The weight of air theoretically required for the combustion of one pound of gas is thus .6857 pounds. For each 20 per cent in excess of this amount (*i. e.*, each .13714 pounds above .6857) there will appear in the products of combustion

$$.13714 \times .2315 = .03175 \text{ pounds } O_2$$
$$.13714 \times .7685 = .10539 \text{ pounds } N_2$$

*While blast furnace gas contains a considerable amount of moisture, varying with the water in the charge and the amount used for dampening, it is customary to give the analysis on a dry basis, reporting the moisture separately in terms of grains per cubic foot of gas. The moisture content is ordinarily about 30 or 35 grains per cubic foot.

and for varying amounts of excess air the weights of the products of combustion per pound of gas will be:

TABLE A

	Weight Products Perfect Combustion	Weight Products—Varying Amounts of Excess Air—Pounds				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	·5734	·5734	·5734	·5734	·5734	·5734
O_2	.0000	.0318	.0635	.0953	.1270	.1588
N_2	1.0902	1.1956	1.3010	1.4064	1.5118	1.6172
H_2O	.0221	.0221	.0221	.0221	.0221	.0221
	1.6857	1.8229	1.9600	2.0972	2.2343	2.3715

Expressed in terms of percentage weight, these values are:

TABLE B

	Per Cent Weight Products Perfect Combustion	Per Cent Weight Products—Varying Amounts of Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	34.016	31.455	29.255	27.341	25.664	24.179
O_2	.000	1.745	3.240	4.544	5.684	6.696
N_2	64.673	65.588	66.377	67.061	67.663	68.193
H_2O	1.311	1.212	1.128	1.054	.989	.932
	100.000	100.000	100.000	100.000	100.000	100.000

Expressed in terms of percentage weight of dry products of combustion, these values are:

TABLE C

	Per Cent Weight Dry Products Perfect Combustion	Per Cent Weight Dry Products—Varying Amounts Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	34.468	31.841	29.589	27.632	25.920	24.406
O_2	.000	1.766	3.277	4.593	5.741	6.759
N_2	65.532	66.393	67.134	67.775	68.339	68.835
	100.000	100.000	100.000	100.000	100.000	100.000

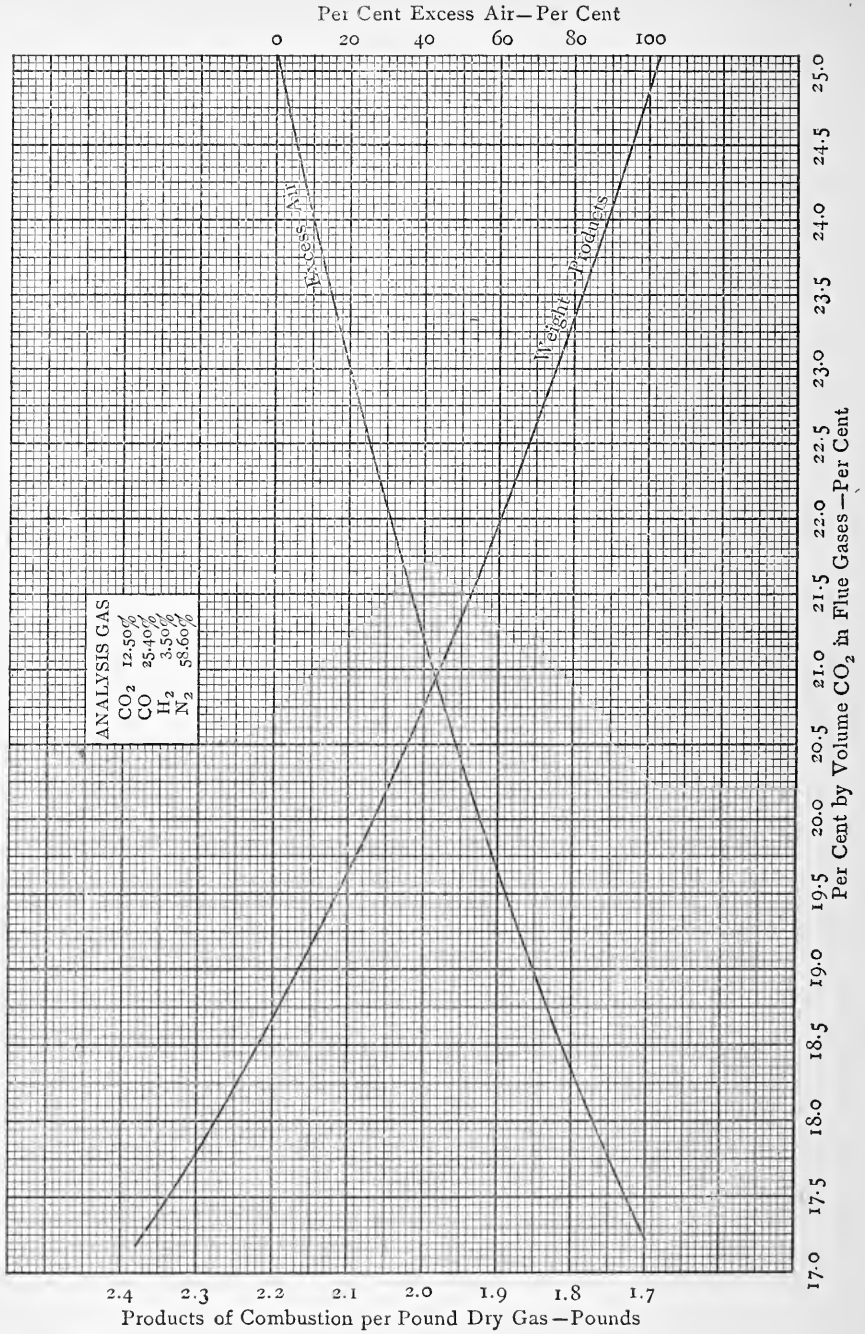

FIGURE 6

BLAST FURNACE GAS. CO_2—Products per Pound Gas
CO_2—Per Cent Excess Air

Converting these percentages by weight of the dry products of combustion into terms of percentage by volume, the values of Table C become:

TABLE D

	Per Cent Volume Dry Products Perfect Combustion	Per Cent Volume Dry Products—Varying Amounts Excess Air				
		20 Per Cent	40 Per Cent	60 Per Cent	80 Per Cent	100 Per Cent
CO_2	25.077	22.973	21.197	19.674	18.357	17.203
O_2	.000	1.752	3.228	4.496	5.590	6.551
N_2	74.923	75.275	75.575	75.830	76.053	76.246
	100.000	100.000	100.000	100.000	100.000	100.000

For the purpose of comparing the results so computed with those obtained from the combustion formulae, assume that the gas is burned with 40 per cent excess air, and that the flue gas analysis shows 21.197 per cent CO_2, 3.228 per cent O_2, and 75.575 per cent N_2.

The weight of dry gas per pound of carbon will be from formula (*27*)

$$\frac{11 \times 21.197 + 8 \times 3.228 + 7 \times 75.575}{3 \times 21.197} = 12.392 \text{ pounds}$$

The weight of carbon per pound of gas burned is

$$\begin{aligned} \text{From } CO_2 \quad .19900 \times \tfrac{3}{11} &= .0518 \\ \text{From CO} \quad .24418 \times \tfrac{3}{7} &= .1046 \\ \text{Total carbon} &= .1564 \text{ pounds} \end{aligned}$$

and the weight of dry products per pound of gas

$$12.392 \times .1564 = 1.938 \text{ pounds}$$

The weight of water vapor formed in the burning of the hydrogen content of the gas will be, per pound of gas

$$9 \times .00246 = .0221 \text{ pounds}$$

and the total weight of the products of combustion per pound of dry gas

$$1.938 + .022 = 1.960 \text{ pounds}$$

which value checks with the computed value of Table A.

Since all of the gas appears in the products of combustion, the weight of air supplied per pound of dry gas burned must be

$$1.960 - 1. = .960 \text{ pounds}$$

which checks with the value computed from the weight of air theoretically required and 40 per cent excess air viz.:

$$.6857 + (.40 \times .6857) = .960 \text{ pounds}$$

Blast furnace gas offers the best example of the unsuitability of formula (*28*) for application in the case of all fuels, for not only is the nitrogen content high (over 50 per cent), but it is large in proportion to the total nitrogen in the products of combustion, even with great amounts of excess air.

If, for the present example, we apply this formula, the weight of air supplied per pound of carbon will be

$$\frac{3.036 \times 75.575}{21.197} = 10.824 \text{ pounds}$$

and the weight of air supplied per pound of gas

$$10.824 \times .1564 = 1.693 \text{ pounds}$$

As compared with the correct weight (.960 pounds) formula (*28*) results in an error of 76.3 per cent, and the error would be still greater were the gas burned with less than 40 per cent excess air.

The heat value per pound of the blast furnace gas, from the analysis by weight and Table 6, is

CO	.24418 x	4380 =	1069.5
H_2	.00246 x	62000 =	152.5
			1222.0 B. t. u.

Since the gas, under standard conditions, weighs as shown, .08121 pounds per cubic foot, the heat value per cubic foot is

$$.08121 \times 1222 = 99.2 \text{ B. t. u.}$$

Or, the heat value per cubic foot, from the volumetric analysis and Table 6, is

CO	.254 x	342 =	86.9
H_2	.035 x	348 =	12.2
			99.1 B. t. u.

If we accept the analysis of blast furnace gas taken as typical of this fuel as a class, the approximate weights of the products of combustion per pound of dry gas burned, and the percentages of excess air, corresponding to various percentages of carbon dioxide, may be determined directly from Figure 6.

HEAT BALANCE

AS in the case of the combustion data just discussed, the computations involved in the determination of the distribution of losses in a boiler test, *i. e.*, the "heat balance," are best illustrated by example.

SOLID OR LIQUID FUELS

Where the weight of fuel burned can be actually weighed, (*e. g.*, coal, oil, or wood) or accurately measured (*e. g.*, natural gas), the computations are direct. The radiation loss and the small losses which cannot be computed from ordinary test data are, as stated, grouped, and are taken as the difference between 100 per cent and the sum of the known and distributable losses.

As an example of this class of heat balance, let us consider one of the tests* at the plant of the Detroit Edison Company, in which the test data and calculated results necessary for the computation of the heat balance were as follows:

Wet Bulb Thermometer, Degrees Fahrenheit		67
Temperature Boiler Room, Degrees Fahrenheit		73
Temperature Exit Gases, Degrees Fahrenheit		575
Ultimate Analysis Dry Coal	C, Per Cent	78.42
	H_2, Per Cent	5.56
	O_2, Per Cent	8.25
	N_2, Per Cent	1.09
	S, Per Cent	1.00
	Ash, Per Cent	5.68
Moisture in Coal, Per Cent		1.91
B. t. u. per Pound Dry Coal		14000
Ash and Refuse (Per Cent Dry Coal)		7.03
Unconsumed Carbon in Ash, Per Cent		31.50
Flue Gas Analysis	CO_2, Per Cent	14.00
	O_2, Per Cent	5.50
	CO, Per Cent	0.42
	N_2, Per Cent	80.08
Evaporation from and at 212 Degrees per Pound Dry Coal, Pounds		11.12

* "Tests of Large Boilers at the Detroit Edison Company."—D. S. Jacobus, Trans. A. S. M. E.—Volume 33.

Heat Absorbed by Boiler

The heat absorbed by the boiler per pound of dry coal is

$$11.12 \times 970.4 = 10791 \text{ B. t. u.}$$

and the efficiency of the boiler

$$10791 \div 14000 = 77.08 \text{ per cent}$$

Loss Due to Moisture in Coal

The moisture in the coal, 1.91 per cent, becomes in terms of dry coal

$$1.91 \div (100 - 1.91) = 1.95 \text{ per cent}$$

and the loss due to this moisture content is

$$.0195\ [(212 - 73) + 970.4 + .48\ (575 - 212)] = 25 \text{ B. t. u.}$$

or

$$25 \div 14000 = 0.18 \text{ per cent}$$

Loss Due to the Burning of Hydrogen

This loss per pound of dry coal is

$$.0556 \times 9\ [(212 - 73) + 970.4 + .48\ (575 - 212)] = 642 \text{ B. t. u.}$$

or

$$642 \div 14000 = 4.58 \text{ per cent}$$

Loss Due to Heat in Dry Chimney Gas

The weight of dry gas per pound of carbon from formula (*27*) is

$$\frac{11 \times 14.00 + 8 \times 5.50 + 7\ (.42 + 80.08)}{3\ (14.00 + .42)} = 17.603 \text{ pounds}$$

The weight of carbon per pound of dry fuel is .7842 pounds. Certain of this carbon, however, is not burned, as evidenced by the unconsumed carbon in the ash. Expressed in terms of total carbon, the unburned weight is

$$.0703 \times .315 = 2.21 \text{ per cent}$$

and the weight of carbon burned per pound of dry coal, and passing off with the chimney gases is

$$.7842 - .0221 = .7621 \text{ pounds}$$

This carbon weight must be further corrected for the sulphur equivalent as previously explained, and applying such correction, the weight of dry gas per pound of dry coal becomes

$$17.603 \times (.7621 + \frac{.01}{1.833}) = 13.412 \text{ pounds}$$

The loss then, due to heat carried away in the dry chimney gases per pound of dry coal is

$$13.412 \times .24 \times (575 - 73) = 1616 \text{ B. t. u.}$$

or

$$1616 \div 14000 = 11.54 \text{ per cent}$$

Loss Due to Moisture in Air

From the wet and dry bulb thermometer readings and psychrometric tables the weight of moisture in the air per pound of dry air supplied is .0127 pounds.

The weight of dry air supplied per pound of dry coal from formula (*28*) is, using as the carbon weight* that which is burned and passes up the stack.

$$\frac{3.036 \times 80.08}{14.00 + .42} \times (.7842 - .0221)^* = 12.849 \text{ pounds}$$

The weight of water vapor per pound of dry coal is

$$12.849 \times .0127 = .163$$

The loss due to the moisture in the air is then

$$.163 \times .48 \ (575 - 73) = 39.3 \text{ B. t. u.}$$

or

$$39.3 \div 14000 = 0.28 \text{ per cent}$$

Loss Due to Incomplete Combustion of Carbon

This loss, from formula (*34*), using the carbon weight actually burned and passing up the stack, and, as in the case of dry chimney gas loss, corrected for the sulphur equivalent, is

$$\frac{0.42}{14.00 + 0.42} \times (.7621 + \frac{.01}{1.833}) \times 10160 = 226.6 \text{ B. t. u.}$$

or

$$226.6 \div 14000 = 1.62 \text{ per cent}$$

*The total loss due to the moisture in the air is so small that there is no necessity of correcting the carbon weight for the sulphur equivalent. In the present case such a correction would not affect the result.

Loss Due to Carbon in the Ash

This loss from formula (*35*) is

$$\frac{.0703 \times 31.5}{100} \times 14600 = 323.3 \text{ B. t. u.}$$

or

$$323.3 \div 14000 = 2.31 \text{ per cent}$$

Radiation and Unaccounted Losses

The radiation and unaccounted losses will be

$$14000 - (10791 + 25 + 642 + 1616 + 39 + 227 + 323) = 337 \text{ B.t.u.}$$

or

$$337 \div 14000 = 2.41 \text{ per cent}$$

The complete heat balance is then

	B. t. u.	Per Cent
Heat absorbed by boiler	10791	77.08
Loss due to moisture in coal	25	0.18
Loss due to moisture formed in burning H_2 .	642	4.58
Loss in dry chimney gases	1616	11.54
Loss due to moisture in air	39	0.28
Loss due to incomplete combustion of C . .	227	1.62
Loss due to unconsumed C in ash	323	2.31
Radiation and unaccounted losses	337	2.41
	14000	100.00

It is of interest to note that the radiation and unaccounted losses for the test considered are as low as 2.41 per cent. Generally speaking, these losses are one of the best indications of the accuracy of a boiler test, and where a heat balance shows an excessive unaccounted loss it is well to scrutinize the test data most carefully before accepting the results without question.

GASEOUS FUELS

With certain gaseous fuels it is impossible accurately to measure the amount of fuel burned without resorting to methods of metering which are not available in most tests. In such cases the heat absorbed by the boiler per unit of fuel burned, and therefore the efficiency of the boiler, cannot be directly determined. Since, however, all of the combustion losses, except,

of course, the radiation and unaccounted loss, can be computed directly, a heat balance not only indicates the distribution of losses, but offers a means of indirectly determining the boiler efficiency. For such determination it is necessary to assume the radiation and unaccounted loss, but experience has fixed the amount of such loss within reasonably accurate limits.

Blast furnace gas is the fuel in most common use that cannot readily be measured, and we will consider a test with this gas in which the data necessary for the computation of a heat balance is as follows:

Temperature Boiler Room, Degrees		60
Temperature Exit Gases, Degrees		550
Analysis Dry Gas by Volume at 60 Degrees	CO_2, Per Cent	13.0
	CO, Per Cent	25.6
	H_2, Per Cent	3.2
	N_2, Per Cent	58.2
Moisture in Gas (Grains per Cubic Foot), Grains		32
Temperature Gas Entering Burner Degrees		300
Flue Gas Analysis	CO_2, Per Cent	21.2
	O_2, Per Cent	3.7
	CO, Per Cent	0.6
	N_2, Per Cent	74.5

We will assume that the radiation and unaccounted loss, including the loss due to the moisture in the air supplied for combustion is 5.0 per cent.

It would, of course, be possible to compute the heat balance either on a volumetric or on a weight basis, but since the common combustion formulae are in terms of weight the latter basis appears preferable.

Converting the analysis of the gas by volume to one by weight, we have

	Volume per Cubic Foot		Weight per Cubic Foot		Weight Pounds				Weight Per Cent
CO_2	.130	x	.12341	=	.01604	÷	.08164	=	19.647
CO	.256	x	.07806	=	.01998	÷	.08164	=	24.473
H_2	.032	x	.00562	=	.00018	÷	.08164	=	.221
N_2	.582	x	.07807	=	.04544	÷	.08164	=	55.659
					.08164				100.000

The weight of the gas then at 60 degrees is .08164 pounds per cubic foot.

The heat value of the gas will be

$$\begin{aligned} .24473 \times 4380 &= 1071.9 \\ .00221 \times 62000 &= 137.0 \\ \text{B. t. u. per pound} &= 1208.9 \end{aligned}$$

or at 60 degrees

$$1208.9 \times .08164 = 98.7 \text{ B. t. u. per cubic foot.}$$

Since the gas enters the boiler at a temperature above that of the atmosphere, there is available in the gas for absorption by the boiler a definite amount of sensible heat aside from the heat developed by the combustion of the gas, and the heat balance therefore must be computed on the basis of above atmospheric temperature.

This sensible heat per pound of gas will be

$$c\ (T - t)$$

where c = mean specific heat of gas,
T = temperature entering gas,
t = temperature atmosphere.

The mean specific heat of the gas between 60 degrees and 300 degrees is

$$\begin{aligned} CO_2 &= .1965(.1983 + .000083 \times 180 - .00000017 \times 37200) = .0398 \\ CO &= .2447(.2343 + .0000105 \times 180) = .0578 \\ H_2 &= .0022(3.29 + .000266 \times 180) = .0073 \\ N_2 &= .5566(.2343 + .0000105 \times 180) = .1315 \\ &\text{Mean specific heat} = .2364 \end{aligned}$$

and the total heat value per pound of gas above 60 degrees is

$$1209 + .2364\ (300 - 60) = 1266 \text{ B. t. u.}$$

The computation of the heat balance proper is as follows:

Loss Due to Moisture in Gas

The gas contains 31 grains of moisture per cubic foot. In terms of weight per pound of gas this value is

$$(1 \div .08164) \times 31 = 379 \text{ grains per pound}$$

or .0541 pounds of moisture per pound of gas.

In terms of weight per pound of dry gas this becomes

$$.0541 \div (1 - .0541) = .0573 \text{ pounds}$$

The loss due to the moisture content of the gas per pound of dry gas burned is then

$$.0573 \times .48\ (550 - 60\ ^*) = 13.48 \text{ B. t. u.}$$

or

$$13.48 \div 1266 = 1.07 \text{ per cent}$$

Loss Due to Burning of Hydrogen

This loss per pound of gas will be

$$9 \times .0022\ [(212 - 60^*) + 970.4 + .48\ (550 - 212)] = 26.88 \text{ B. t. u.}$$

or

$$24.43 \div 1266 = 1.93 \text{ per cent}$$

Loss Due to Heat in Dry Chimney Gases

From the flue gas analysis and formula (*27*) the weight of dry gas per pound of carbon burned is

$$\frac{11 \times 21.2 + 8 \times 3.7 + 7\ (74.5 + .6)}{3\ (21.2 + .6)} = 12.398 \text{ pounds}$$

The weight of carbon per pound of dry gas burned is

$$\begin{aligned} \text{From } CO_2 \quad & .19647 \times \tfrac{3}{11} = .05358 \\ \text{From } CO \quad & .24473 \times \tfrac{3}{7} = .10488 \\ & \text{Total C} = .15846 \text{ pounds} \end{aligned}$$

and the weight of dry products of combustion per pound of gas burned

$$12.398 \times .15846 = 1.965 \text{ pounds}$$

The loss in dry chimney gases is then

$$1.965 \times .24\ (550 - 60) = 231.08 \text{ B. t. u.}$$

or

$$231.08 \div 1266 = 18.25 \text{ per cent}$$

* The temperature of the atmosphere is used rather than the temperature of the gas entering the burners, since the heat balance is based on the total heat per pound of gas above atmospheric temperature.

Loss Due to Incomplete Combustion of Carbon

This loss from formula (*34*) is

$$\frac{.6}{21.2+6} \times .1585 \times 10160 = 44.30 \text{ B. t. u.}$$

or

$$44.30 \div 1266 = 3.50 \text{ per cent}$$

The heat absorbed by the boiler per pound of gas burned, by difference, assuming the radiation and unaccounted loss as 5.0 per cent or 63.30 B. t. u., is

$$1266 - (13.48 + 24.43 + 231.08 + 44.30 + 63.30) = 889.41 \text{ B. t. u.}$$

or

$$886.96 \div 1266 = 70.06 \text{ per cent}$$

The complete heat balance is then

	B. t. u.	Per Cent
Loss due to moisture in gas	13.48	1.07
Loss due to moisture formed in burning H_2 .	24.43	1.93
Loss in dry chimney gases	231.08	18.25
Loss due to incomplete combustion of C . .	44.30	3.50
Radiation and unaccounted loss (assumed) .	63.30	5.00
	376.59	29.75
Absorbed by boiler (by difference)	889.41	70.25
	1266.00	100.00

The above method may be followed for any fuel where an actual weight or measurement of fuel is not possible, but where such weight or volume can be determined the method used in the case of coal, preceding, is preferable.

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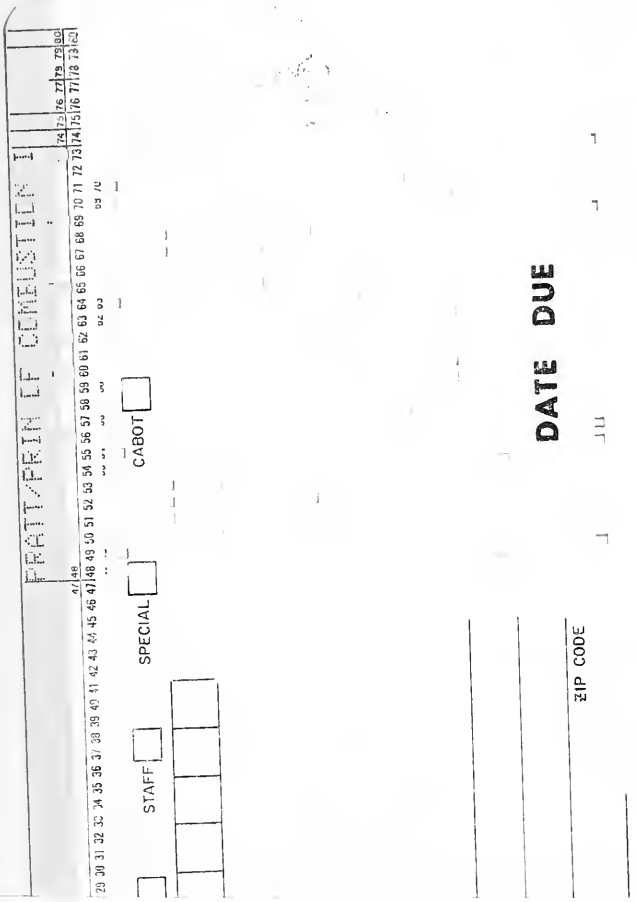

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